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M.V. ARCTIC
Manoeuvring Performance in Ice
INTERIM REPORT
TP-5318E

Prepared for
Transportation Development Centre
Montreal, Quebec

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PROJECT TEAM

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DISCLAIMER

The contents of this report reflect the views of the authors and not necessarily the official views or policies of the Transportation Development Centre.

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17. Abstract

This Interim Report has been prepared roughly two-thirds of the way through a project aimed at determining the Manoeuvring and control characteristics of the M.V. Arctic in ice. Analysis is based on the records accumulated over the period 1979-81, when the ship was equipped with a computerized data acquisition system. These records have been processed, the extent of the data base established, and sufficient analysis performed to identify areas in which detailed evaluations and performance assessments will be possible. Various preliminary suggestions for theoretical and practical approaches to the problems of manoeuvring in ice have been put forward. These problems are such that in ice above a certain thickness, it will not be possible to effectively manoeuvre most ships by conventional use of the rudder alone.

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17. Résumé

Ce rapport concerne la manoeuvrabilité et le comportement de l'Arctic dans les glaces. Il s'agit d'un rapport provisoire portant, grosso modo, sur les deux premiers tiers du projet. Les résultats rapportés sont tirés des données enregistrées entre 1979 et 1981 au moyen du système de saisie automatique des données dont ce navire était équipé. La base de données de la présente étude a été délimité après traitement initial de ces données, puis l'analyse a été poussée au point de pouvoir situer dans la masse des données celles qui pourront servir à l'analyse et à l'évaluation détaillées de la tenue du navire. Le rapport propose également différentes approches possibles pour l'étude théorique et pratique des problèmes liés à la manoeuvre des navires dans les glaces. Ces problèmes sont tels que, au-delà d'une certaine épaisseur des glaces, les méthodes classiques de manoeuvre par gouvernail ne répondent plus aux exigences.

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1.0 INTRODUCTION

The M.V. Arctic was constructed to Canadian Arctic Shipping Pollution Prevention Regulations, Class II, as a forerunner for future generations of Arctic waters shipping. Her principal particulars are given in Table 1.1 below. Establishing her performance and capabilities has, therefore, been recognized since her genesis as a task of considerable importance, and a number of projects have been commissioned to yield this data.

One major area of effort was the installation and operation over three seasons (1979 - 81) of a computerized data acquisition system / 1 / which was used to measure and record a variety of data, both in normal operations and in a number of dedicated ice trials. The Transportation Development Centre (TDC) of Transport Canada has commissioned a set of studies into various areas of performance monitored by this system. Amongst these is the manoeuvring performance study, for which this is the interim report.

The manoeuvrability of ships in ice is a subject which has hitherto received little systematic attention. Unfortunately, it was also only given secondary consideration when designing the data acquisition system and when planning the field tests programs. The limited extent of the resulting data base is described below. It has none the less yielded a number of interesting results, the analysis of which is also discussed and will be reported in full in the final project report.

TABLE 1.1

M.V. ARCTIC - TECHNICAL DATA

Length Overall	209.55	metres
Length between Perpendiculars -	196.60	metres
Moulded Breadth	22.86	metres
Moulded Depth	15.24	metres
Moulded Draught	10.97	metres
Summer Draught	10.82	metres
Block Coefficient	0.753	
Prismatic Coefficient	0.761	
Light Ship	9,276.1	tonnes
Displacement at 10.82 m. Draught	37,724.1	tonnes
Deadweight at 10.82 m. Draught	28,448.0	tonnes
Cargo Capacity	36,490.8	cubic metres
Propulsion Machinery - MAN Diesel	11,014	kilowatts
Generators	900	kW x 3
Complement	40	
Speed on Trials	15.5	knots
Cruising Range	14,000	Nautical miles

2.0 SHIP MANOEUVRABILITY AND CONTROL - BACKGROUND

2.1 General

The ability to maintain a desired course and to change it as necessary in a timely and predictable fashion are obviously important attributes for any ship in any operating environment. Both are dependent on the characteristics of the hull and of the steering gear system. In general the designer will choose a steering gear configuration after considering the probable performance of the hull, basing any predictions on a variety of more or less empirical formulae and/or model testing. The chosen system will have to comply with criteria covering component strength, speed of response, redundancy, and in some cases control surface size; these criteria being loosely related to the ship configuration and the likely loading regime.

Naval architects thus have considerable freedom in choosing a level of manoeuvring performance for any ship type, with the result that considerable differences exist between otherwise comparable ships. The choice of what constitutes adequate manoeuvrability in any application remains essentially subjective. Since many ship casualties are related to manoeuvrability and steering gear performance, it is open to question whether this traditional approach is satisfactory.

The situation described above covers both open water operations and those in ice, the principal differences being that in ice performance prediction has little basis other than guesswork, and that the regulatory criteria (Appendix 'A') are even less well founded on likely actual requirements. The objectives for this study were mainly directed towards these two areas. An evaluation of the performance of the M.V. Arctic and an understanding of the influences involved should be relevant to all future similar ice-capable shipping.

Before turning to performance in ice, it is sensible to consider manoeuvrability and control in open water. The influence of various parameters differs in the two cases, and for most ice-capable ships which will spend the majority of voyage time in open water this case is of at least equal importance. A successful design will, therefore, have to make compromises between two different optimum configurations.

2.0 SHIP MANOEUVRABILITY AND CONTROL - BACKGROUND (Cont'd)

2.2 Open Water Manoeuvrability Predication

No completely satisfactory theoretical model of steady-state resistance and propulsion has yet been developed. It is, therefore, not surprising that manoeuvrability prediction remains still more dependent on model testing and empirical approximations. It is a considerably more complex subject not only in terms of the number of parameters involved, but also because a complete description of performance has to account for the extremely non-linear transient phases of any turn as well as the subsequent steady-state stages.

Starting with a basic, qualitative approach the influence of a number of the more important ship characteristics on manoeuvrability is indicated by Table 2.2.1 (from a number of sources, including Refs. 2, 3, 4 and 17). This type of information can be used at the earliest stages of design to assess the probable manoeuvring characteristics of the vessel, and consequently the steering gear configuration which will be required to give an acceptable level of performance. Due consideration also has to be given to environmental conditions in the ships intended operating areas; as wind, waves and currents can have major impacts on manoeuvrability.

Some basic empirical formulae have been developed relating manoeuvrability to certain of the factors in Table 2.2.1, but much more value is found in approaches using the manoeuvring equations of motion. These can be formulated with any desired level of complexity; for practical purposes the simple form below is often found adequate.

Equations of motion (from Ref. 2).

$$-Y'_{\dot{v}}\dot{v}' + (m'-Y'_{v})v' - (Y'_{r} - m')r' - (Y'_{\dot{r}} - m'x'_{G})\dot{r}' = 0$$

$$-N'_{\dot{v}}\dot{v}' - (N'_{v} - m'x'_{G})v' - (N'_{\dot{r}} - m'x'_{G})\dot{r}' + (I'_{z} - N'_{r'})r' = 0$$

(for definition of symbols see Section 9.0)

2.0 SHIP MANOEUVRABILITY AND CONTROL - BACKGROUND (Cont'd)

2.2 Open Water Manoeuvrability Predication (Cont'd)

All the coefficients can be identified from model tests using rotating arms and/or planar motion mechanism. They can also be estimated from mathematical modelling of the ship hull. In its purest forms, this can be disproportionately expensive compared to the accuracy of the results achieved, but the less rigorous approximate formulae described in / 2 / can give useful information for some important aspects of ship performance relatively easily through predicting values for the linear coefficents.

The linear terms have been computed for the M.V. Arctic, yielding the values below:

$Y'v = -0.390$

$N'v = -0.098$

$Y'r = 0.076$; $m' - Y'r = 0.100$

$N'r = -0.064$

The significance of these values is addressed in later sections.

TABLE 2.2.1
Ship Characteristics Affecting Manoeuvrability in Open Water

CHARACTERISTIC	INFLUENCE
L/B	Increase reduces manoeuvrability.
L/D	Increase increases manoeuvrability.
C_B	Increase increases manoeuvrability.
Forefoot Shape	Sharp forms reduce manoeuvrability.
Fixed Fins	Depends on position-in general fins aft reduce manoeuvrability.
Stern trim	Increase reduces manoeuvrability.
No. of Propellers	Single screw forms more manoeuvrable.
Propeller Type	Ducts, high RPM reduce manoeuvrability.

Note: This describes the basic situation. Certain ship forms or propeller selections which tend to reduce manoeuvrability may allow the choice of more efficient rudder configurations. Thus, for example, single-screw ships can often be outperformed by vessels with multiple shafts.

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2.0 SHIP MANOEUVRABILITY AND CONTROL - BACKGROUND (Cont'd)

2.3 Open Water Steering Gear Selection

As with other areas of ship design, steering gear selection is a set of compromises between cost, reliability, performance, etc. The overall configuration is generally dictated by the hull form, with propeller arrangements another major consideration.

The major constraints on the designer are those imposed by classification societies and national and international regulations on the strength and redundancy of the steering gear related to loads which can be generated by the normal operation of the ship, with little consideration of external hazards. The only precaution against such hazards which is generally taken is to keep any rudder within the maximum draught and beam of the ship, to protect it from impact with docks or the sea bed. Steering gear emergencies are most usually due to failure of internal components such as the hydraulic or control systems, for which newbuilding regulations now require adequate back-ups.

2.4 Previous Studies in Ice

Manoeuvrability and control in ice have received much less attention than have other ice-related issues, but a fairly large number of reports and papers have now commented on at least some aspects of the subject. The most useful of these are given in the list of References. Some conclusions from these are shown in Table 2.4.1, which should be compared with Table 2.2.1 developed for the open water case. Others are discussed in later Sections where they are compared to results obtained with the M.V. Arctic.

TABLE 2.4.1

Ship Characteristics Affecting Manoeuvrability in Ice

CHARACTERISTIC	INFLUENCE
L/B	Increase reduces manoeuvrability.
C_B	Increase reduces manoeuvrability.
Forefoot shape	Controversial

3.0 M.V. ARCTIC MANOEUVRING DATA BASE

3.1 Selection of Data Categories/Performance Characteristics

The selection of data categories has been made on the basis of:

a. Those parameters that influence manoeuvring performance, and
b. The performance characteristics assessed to be of importance to the operator or the designer.

Those parameters influencing performance can be further divided into two groups:

a.1) Environmental Factors:

- Ice characteristics such as thickness, strength, distribution, pressure, snow cover.
- Surface current speed, direction, water depth.
- Wind speed, relative direction.

a.2) Controllable variables:

- Shaft power and RPM.
- Rudder angle.
- Bubbler status.
- Ship condition such as draft, trim and heel.

Performance characteristics that are useful and important to the operator can again be divided into two groups.

b.1) Open sea operation.

In this condition, the manoeuvring capabilities of significance are those that permit the vessel to keep to a selected heading and those that allow that heading to be to be changed in the most economical manner. These capabilities, in terms familiar to the operator, may be expressed as:

i) Basic directional stability.
ii) Rate of change of heading for a given angle of helm at a certain speed.
iii) Advance and transfer during a specified heading change.
iv) Responsiveness of the rudder to commands given.
v) Risk to the rudder, given the surface conditions (ice presence).

b.2) Restricted waters operation.

The behaviour and response of the vessel in harbours or in other restricted conditions is also of great importance to the operator. The ability to change heading at low or even zero speed is crucial when unassisted docking is a consideration. Reliable control of direction when moving astern and rapid response of the steering system are also of importance in such conditions. The capabilities may thus be expressed as:

i) Low speed directional stability (ahead and astern).
ii) Low speed rate of change of heading, including bubbler or thruster assistance.
iii) Steering gear responsiveness.

In summary, the data categories may be indicated as follows in two groups:

A. Environmental:

- Open water
- Level continuous ice
- Mixed ice

3.0 M.V. ARCTIC MANOEUVRING DATA BASE (Cont'd)

3.1 Selection of Data Categories/Performance Characteristics (Cont'd)

B. Manoeuvring:

- continuous ahead motion
- Astern motion
- Restricted condition operation

and the performance characteristics as:

- Turning performance.
  (Rate of change of heading, advance, transfer, turn diameter during specified heading change).
- Directional stability
  (Ability to maintain fixed heading)
- Astern performance
- Responsiveness of rudder and steering gear to commands issued.
- Risk to integrity of rudder and steering gear system.
- Influence of bubbler.

3.2 Scanning Procedures

As a preliminary task in the analysis of the M.V. Arctic data base, a review of the current documentation was performed to determine the quantity of relevant data available for reduction and subsequent analysis. The Master Data Package / 23 / was used as the principal reference document. These volumes comprise detailed descriptions of the data tapes; including information on the reasons for data gathering, ice, environmental conditions, data acquisition system parameters, sensor status and conversion equations for each sensor. A statistical summary of each data tape is provided, which proved useful in the validation of data after the transfer to flexible disk. To acquire any relevant information absent from the Master Data Package, the reports submitted by the various operators of the system were consulted.

3.0 M.V. ARCTIC MANOEUVRING DATA BASE (Cont'd)

3.2 Scanning Procedures (Cont'd)

The data base collected on board the M.V. Arctic consists of 163 magnetic tapes collected during the 1979-1981 operating seasons. The data was acquired both during the normal operating voyages and during several dedicated ice trials performed to assess ships performance in ice. In view of the broad spectrum of data collected, only those tapes judged to contain data relevant to ships manoeuvring performance were selected for processing. These tapes are listed in Table 3.2.1.

The data acquisition system can accommodate upto 256 discrete sensor inputs for data gathering. Of these, eighteen were selected as containing information pertinent to ships manoeuvring performance.

The sensors selected for extraction are as follows:

- Sway forward (channel 2)
- Rudder stock strain (channel 196) **
- Thrust (channel 198)
- Rudder angle response (channel 200)
- Differential rudder pressure (channel 202) *
- Shaft torque (channel 208)
- Shaft RPM (channel 209) *
- Shaft RPM (channel 211) **
- Sway aft (channel 213)
- Sway aft, filtered (channel 216) *
- Wind speed (channel 233)
- Wind direction (channel 234)
- Ships speed (channel 236)
- Ships heading, cosine (channel 237)
- Ships heading, sine (channel 238)
- Pitch angle (channel 239) **
- Roll angle (channel 240)
- Rudder command (channel 245)

N.B. * - 1979 - 1980 Seasons only
** - 1981 Season only

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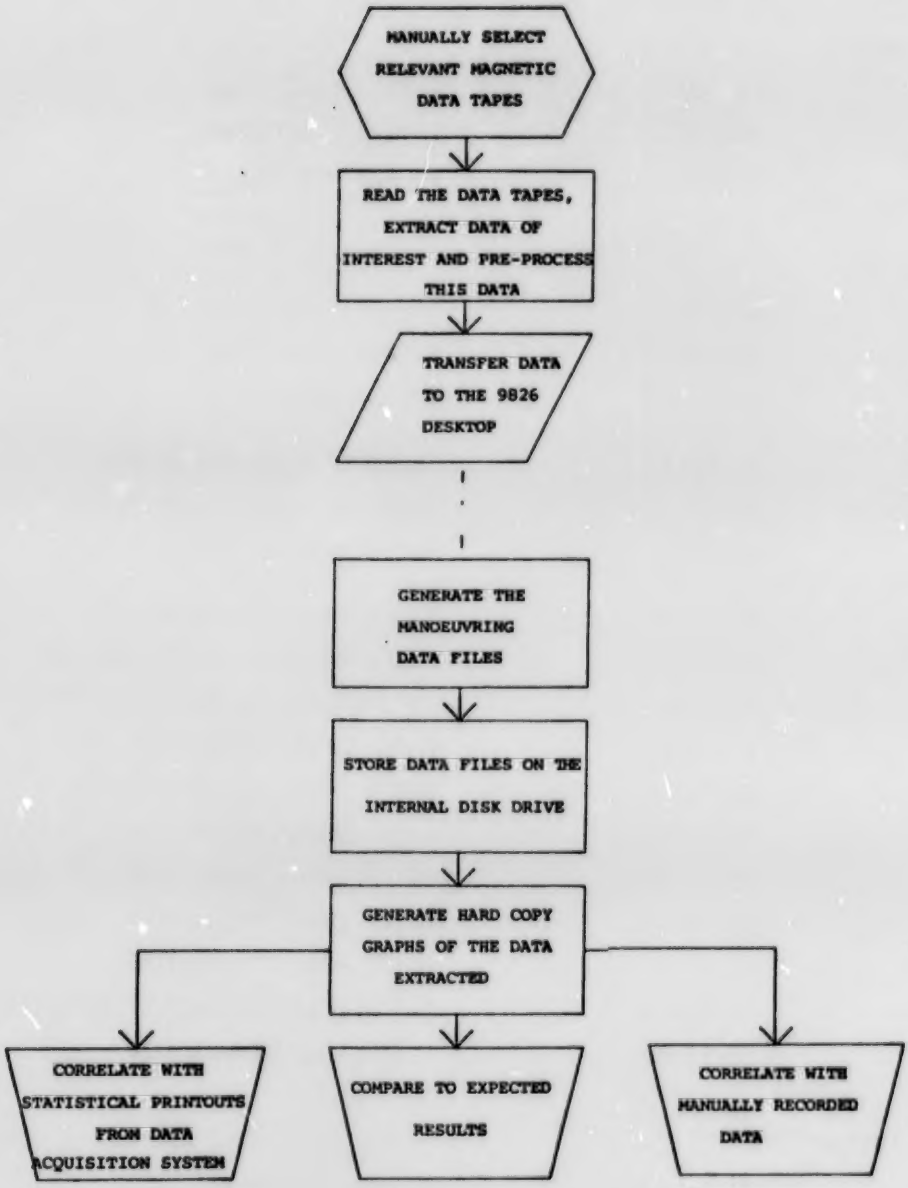
TABLE 3.2.1

Tapes Chosen for Data Reduction

Note: Dedicated trials have been assigned an identifier, D1-D24 for ease of reference.

1979:-		
	79-7-34	Voyage monitoring
	79-7-37	Voyage monitoring
	79-7-31	Voyage monitoring
1980:-		
	80-1-2	Voyage monitoring
	80-1-9	Voyage monitoring
	80-6-20	Voyage monitoring
	80-T1-1	Saguenay River Trials; D22
	80-T1-3	Saguenay River Trials; D23
	80-T1-9	Saguenay River Trials; D24
	80-T2-2	Baffin Island Trials; D5, D6
	80-T2-5	Baffin Island Trials; D7, D8, D9
	80-T2-6	Baffin Island Trials; D10
	80-T2-8	Baffin Island Trials; D11
	80-T2-9	Baffin Island Trials; D12 D13
	80-T2-10	Baffin Island Trials; D21
	80-T2-11	Baffin Island Trials; D14
	80-T2-13	Baffin Island Trials; D15
	80-T2-14	Baffin Island Trials; D16
	80-T2-19	Baffin Island Trials; D17, D18, D19
	80-T2-20	Baffin Island Trials; D20
1981:-		
	81-1-7	Voyage monitoring
	81-9-16	Voyage monitoring
	81-10-36	Voyage monitoring
	81-T1-12	Lake Melville Trials; D1, D2
	81-T1-13	Lake Melville Trials; D3
	81-T1-14	Lake Melville Trials; D4
	81-T1-15	Lake Melville Trials; D3


MANUALLY SELECT RELEVANT MAGNETIC DATA TAPES
READ THE DATA TAPES, EXTRACT DATA OF INTEREST AND PRE-PROCESS THIS DATA
TRANSFER DATA TO THE 9826 DESKTOP
GENERATE THE MANOEUVRING DATA FILES
STORE DATA FILES ON THE INTERNAL DISK DRIVE
GENERATE HARD COPY GRAPHS OF THE DATA EXTRACTED
CORRELATE WITH STATISTICAL PRINTOUTS FROM DATA ACQUISITION SYSTEM
COMPARE TO EXPECTED RESULTS
CORRELATE WITH MANUALLY RECORDED DATA

DATA REDUCTION & PRELIMINARY VALIDATION OVERVIEW

TABLE 3.2.2

3.0 M.V. ARCTIC MANOEUVRING DATA BASE (Cont'd)

3.2 Scanning Procedures (Cont'd)

Due to the status of certain transducers, some channels were only operative during specific time periods. During any given period only fifteen of the above sensors were extracted from the data tapes.

3.3 Data Reduction and Validation

The data reduction was performed using a Hewlett-Packard 1000 Mainframe and a Hewlett-Packard 9826 Desktop Computer. The transfer of the data from the magnetic tapes to the diskettes was carried out at the Hewlett-Packard facility in Kirkland, Quebec. All subsequent processing was conducted in-house using the H.P. 9826. The software developed for the data reduction and validation consists of three programs:

1. The data retreival and reduction program.
2. The H.P. Asynchronous terminal emulator package.
3. The data validation and analysis software.

1. Data Retrieval & Reduction

The data retrieval and reduction program is written in the high level FORTRAN language and is executable on the H.P. 1000 Mainframe computer. This program reads the data tapes, extracts samples from the sensors of interest, condenses the data to one mean value per sensor per half second interval and then relays the data to the 9826 Desktop via a RS232 serial communications interface. Data is transferred in its original form (i.e. unconverted binary "N" number), thereby retaining the ability to modify conversion consistants or correction factors in-house should new values become available at a later time.

Although the data tapes exhibited certain anomalies, such as bad header blocks, bad data blocks or parity errors, the data scanning software was developed to extract data between user defined start and stop times, therefore enabling any inaccessible data to be omitted without losing the rest of the data on the tape.

2. The Asynchronous Terminal Emulator

The Hewlett-Packard Asynchronous terminal emulator software runs on the H.P. 9826 Desktop Computer. This package enables the Desktop to simulate the I/O Protocol of the Mainframe computer, thereby permitting direct transfer of ASCII data files from the Mainframe to the H.P. 9826. Once received, the data is stored on the internal floppy disk of the Desktop unit.

3. Data Validation and Preliminary Analysis

To ensure the validity of any analysis carried out on the information extracted from the Magnetic tapes, it was felt that this data should be validated to ensure that it was indeed accurate. A preliminary validation program was written on the H.P. 9826 Desktop computer to generate hardcopy graphs of the Data files. In order to convert the raw data to engineering units, each data sample is adjusted using the appropriate conversion equation and stored in the core memory of the 9826 Desktop (See Table 3.3.1). Upon completion of the Saguenay River Trials, it was noted that the tapes exhibited inconsistences when processed. After some study it was determined that during these trials Box 5 was switched off. This absence caused significant voltage shifts throughout the data acquisition system, thereby introducting errors in the data recorded. Each bin of the data acquisition system was affected to a different degree by the absence of box 5, therefore, one of sixteen bin correction factors was used depending on the sensor being examined. A correction subroutine was written for the data acqusition system playback program to compensate for these inaccuracies. The algorithm for this routine was incorporated into the data verification and analysis software.

The program is capable of plotting up to four sensors simultaneously on a variable time base scale. These graphic representations proved to be an effective tool in examining both the individual data signals as well as the

TABLE 3.3.1

Conversion Equations

Parameter	Channel	Conversion Equation			
		1979	1980	March 1981 (Lake Melville Trials)	1981 Season
Sway Forwared	2	.048N-24.5	.048N-24.5	.048N-24.5	.048N-24.5
Rudder Stock Strain	196			2.2133N-1132	2.2133N-1132
Thrust	198	2.4N-1155.7	2.29N-1176	2.29N-1176	2.29N-1176
Rudder Angle Response	200	.0781N-40	.0781N-40	.0781N-40	.0781N-40
Differential Rudder Pressure	202	.0336N	.032N		
Shaft Torque	208	.92N-320.1	1.475N-151.04	1.803N-185	1.475N-151.04
Shaft RPM	209				
Shaft RPM	211			61140/N+18.4	61140/N+18.4
Sway aft	213	.048N-24.5	.048N-24.5	.048N-24.5	.048N-24.5
Sway aft (filtered)	216		.048N-24.5		
Wind Speed	233	.14N-69.5	.136N-69.5	.136N-69.5	.139N-71.4
Wind Direction	234	-.35N+296	-.35N +360	-.35N+360	-.35N+360
Ships Speed	236	.0196N+.86	.03N	.0293N	.03N
Ships Heading (Cosine)	237	N-512	N-512	N-512	N-512
Ships Heading (Sine)	238	N-512	N-512	N-512	N-512
Pitch Angle	239			.01N-5	.02N-10
Roll Angle	240			.01N-5	.02N-10
Rudder Command	245	.0781N-40	.0781N-40	.0781N-40	.0781N-46.25

N.B. All tapes recorded during the Saquenay River Trials must be adjusted by the Appropriate correction factor, see Table 3.3.2.

TABLE 3.3.2

Saguenay River Trials Correction

BINARY COMPUTER "N" NUMBER	CORRECTION
N = 0 - 64 N = 960 - 1024	N = N * bin correction factor
N = 65 - 214 N = 810 - 959	N = TRIAL(INT ((N - 61.44))/2.55) * bin correction factor
N = 214 - 511 N = 513 - 810	N = (2.22 N - 170) * bin correction factor

N.B. TRIAL (n) is a sixty element array containing correction coefficients for the non-linar ranges of the signal.

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behaviour of interdependant signals such as rudder command and rudder response or ships heading and wind speed. The variable time base option allowed for an "expanded" view of segments of interest. In addition to the visual inspection of the data, the information additional verification was performed by correlating with the data acquisition statistical printouts and manually recorded data when available. Sample plots for same of the relevant manoeuvring parameters are included in Appendix B.

4. Data Quality

The quality of the data extracted has been examined for its reliability and usefulness for analysis:

a. Heading. These values vary from 0° to 360° as is to be expected. Actual values compare well with heading information on maps of several test runs and with log information.

b. Rudder Command and Response. These two channels show values that cross check well in most trials. Rudder actions are compatible with heading changes.

c. Ship Speed. The doppler log is known to be unreliable at slow speeds. Also the small speed changes associated with turning are not reliably observable from the records. However, the data, plus correction factors obtained by other investigations serve to provide an indication of relative speed in various tests and ice conditions. Since negative speeds do not show up, astern motion velocities are not available.

d. Wind Speed and Direction. Values do not generally correspond with those indicated in the Master Data Package or log. Changes in relative direction are, however, compatible with heading changes. At this time, the effects of the winds recorded on the ships manoeuvrability do not appear to have been significant.

e. Shaft RPM. Only late '81 season data is available. A delay in extracting this data has resulted in its not having received close attention at this time. Approximation of RPM based on thrust and torque data in association with propeller test information has resulted in values of the order to be expected on this installation. The absence of RPM data is seen as a major flaw and limits the analysis which can be performed in several areas.

f. Torque. No alternate measurement of torque is recorded. However, using torque and RPM (where available) to compute power resulted in maximum powers slightly in excess of installed power on the vessel.

g. Thrust. Data on thrust was used with torque data to estimate RPM as indicated above. If suitable relationships between thrust power and speed can be obtained from other studies, thrust may be a useful parameter for further analysis of the manoeuvring records.

h. Sway Fwd and Aft. There is considerable noise on these channels. The unfiltered and filtered signals show significant differences. Usefulness of these channels is minimal.

i. Rudder Differential Pressure. The recorded values are virtually unchanging under all conditions. This data not to be considered further.

j. Rudder Stock Torque; Propeller Pitch. This data extracted but not examined at this time.

k. Roll. Roll periods are consistent with the vessel size and type. Numerical amplitude of heel does not always coincide with logged values. The available information is not considered useful for this analysis.

3.0 M.V. ARCTIC MANOEUVRING DATA BASE (Cont'd)

3.4 Extent of Available Data

As discussed above, data categories were selected at the commencement of the project and the Master Data Package and other reports were scanned to assess which data tapes should be analyzed to provide relevant information. It rapidly became apparent that only a very limited range of data would be available. This has been reduced still further by the poor quality of the signals from a number of important sensors, and by deficiencies in the data acquisition system operating techniques. In view of the small number of manoeuvring tests performed, it is particularly unfortunate that most of these were not recorded in full, and some were not recorded at all other than in manual records taken on the bridge. Acquisition strategies will be discussed in more detail in Section 6.0 and in the final project report.

Almost all of the useful data on actual manoeuvres comes from the trials off Baffin Island, in Lake Melville, and in the Saguenay River, listed in order of value. This is supplemented by some results from the Builders Trials, and the voyages monitoring records which mainly cover ahead motion in ill-defined ice. This information falls into some but not all of the original categories namely:

Open Water:	Continuous ahead
	Course alterations
Homogeneous Ice:	Continuous ahead
	Course alterations
	Astern

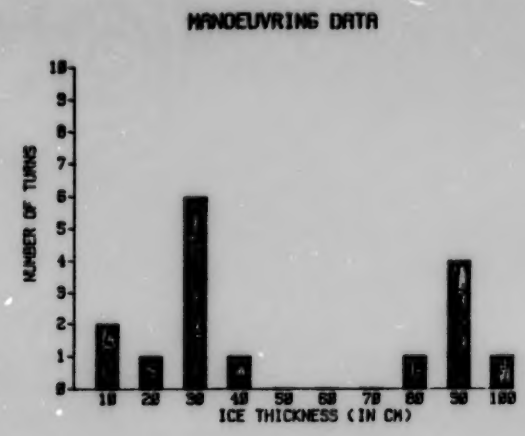
Only these can, therefore, be discussed on the basis of actual results.

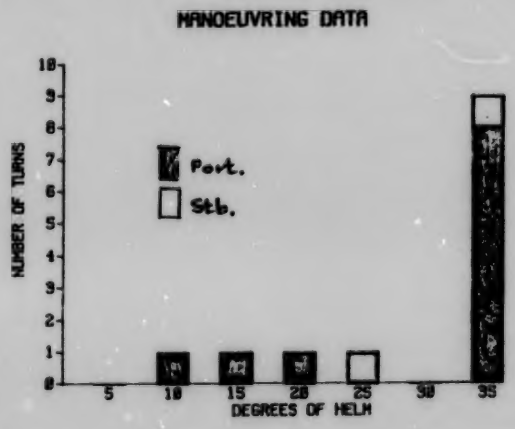
Of the important environmental conditions and controllable variables, only a few have changed or have been changed sufficiently to give an assessment of these influences, these being:

Ice thickness
Shaft power
Rudder angle

The histograms of Figure 3.4.1 show the range of variation for each of these in the manoeuvring records. Due to the gaps in the data base the number of samples in each group tends to vary somewhat.

Data quality from the sensors relevant to manoeuvring has been described in Section 3.3. The information which is completely lacking is that providing information on rigid body motions. Very limited results are available for sensors relevant to rudder/ice interactions. The other parameters were recorded in sufficient detail, but the accuracy of certain sensors is frequently questionable. On some occasions, particularly during the Baffin Island Trials and to some extent in Lake Melville, the bridge radar records provide valuable additional information (Refs. 18, 19) which has been used to fill gaps in the taped records.


MANOEUVRING DATA
NUMBER OF TURNS
ICE THICKNESS (IN CM)


MANOEUVRING DATA
NUMBER OF TURNS
Port.
Stb.
DEGREES OF HELM

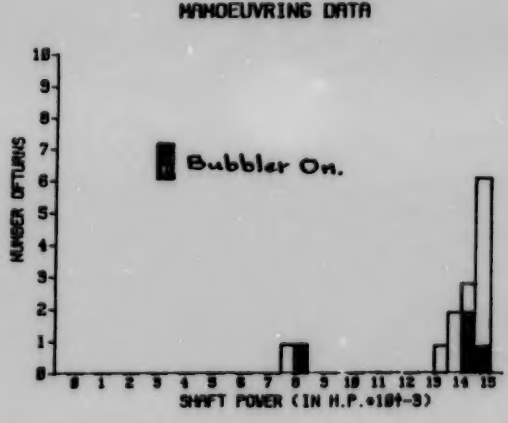

MANOEUVRING DATA
NUMBER OFTURNS
Bubbler On.
SHAFT POWER (IN H.P.*10**-3)

Figure 3.4.1

4.0 M.V. ARCTIC MANOEUVRING PERFORMANCE ANALYSIS

4.1 Turning Performance

A number of standard manoeuvring tests are used to give a picture of a vessel's performance in open water. Three of these; the turning circle test, spiral manoeuvre, and Kempf manoeuvre, are shown in Figures 4.1.1, 4.1.2 and 4.1.3 noting the important quantities which are usually recorded. For most ships a limited set of trials is performed, normally at full speed, and the information obtained is regarded as sufficient to assess the adequacy of manoeuvrability under other likely operational conditions. Ships with auxiliary thrusters and/or unusually stringent positioning or course-keeping requirements are likely to undertake more and different tests as appropriate.

The only standard manoeuvre which the M.V. Arctic has recorded in both ice and open water is the turning circle. (Other manoeuvres have been made, but only a small amount of relevant information was measured). The first question which must be addressed is whether the important quantities measured in open water are still useful or sufficient performance indicators in ice.

An open water turn is characterized by an initial transient phase, during which values of speed, rate of turn, heel angle, and various other quantities go through certain changes. This is followed by a steady phase in which they remain constant. Pull-out from a turning circle can be regarded as a third phase, but is not normally studied in consistent or detailed fashion.

In ice the first two phases can still be identified, though their characteristics are different. To illustrate this, the heading angle and velocity records for two turns, one in open water and the other in ice are compared in Figure 4.1.4. It is immediately apparent from the scatter about the trend lines shown that turning in ice never becomes a smooth, continuous process. Just as for ahead motion, turning in ice is dependent on the failure of the ice sheet, which occurs as a succession of discrete events. The basic frequency of these will presumably be dependent on ice strength and thickness and on ship velocity, as also will be the magnitude of fluctuations about mean values of speed, rate of turn, etc. It should be possible to relate

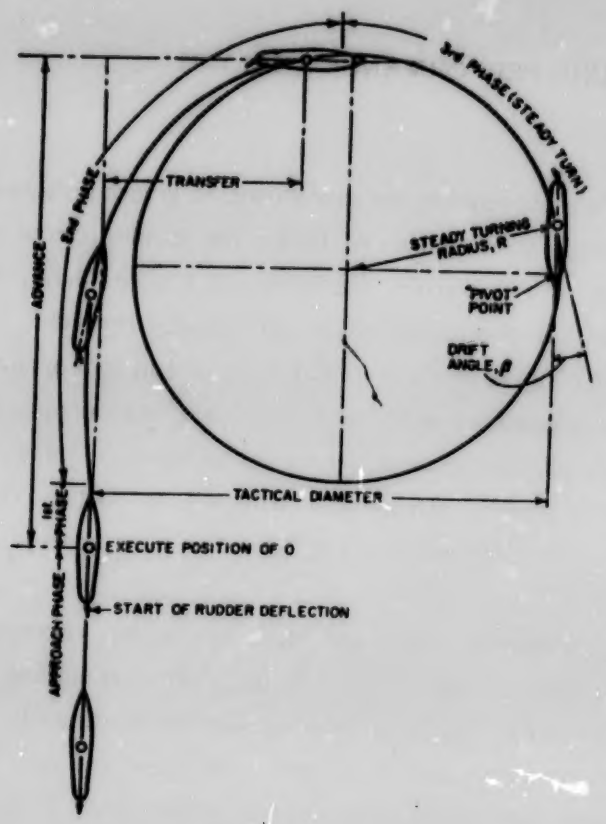


FIG.4.1.1a - Schematic Form of Turning Radius Manoeuvre

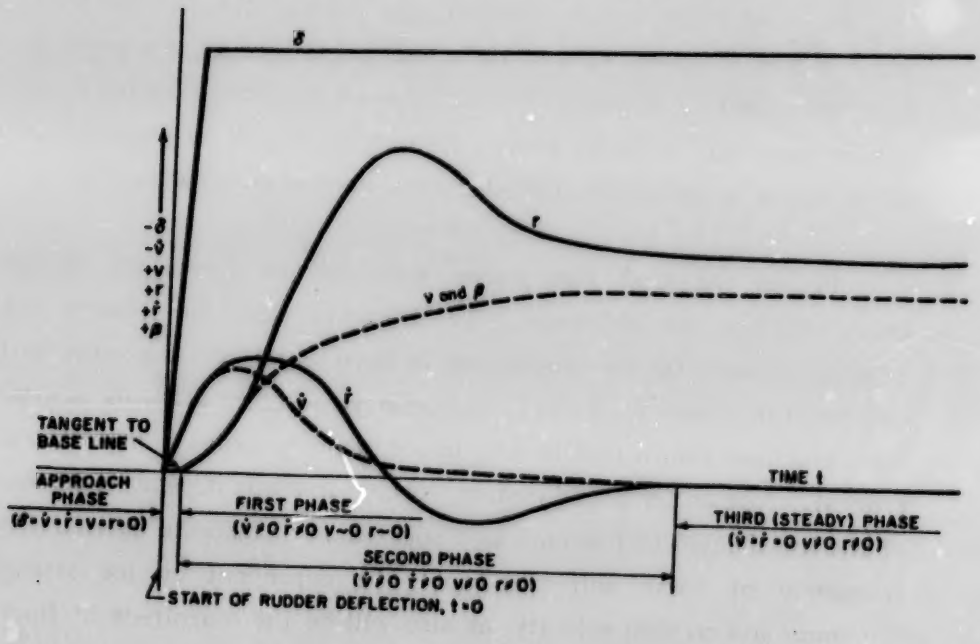


FIG.4.1.1b - Typical Results of Turning Radius Manoeuvre

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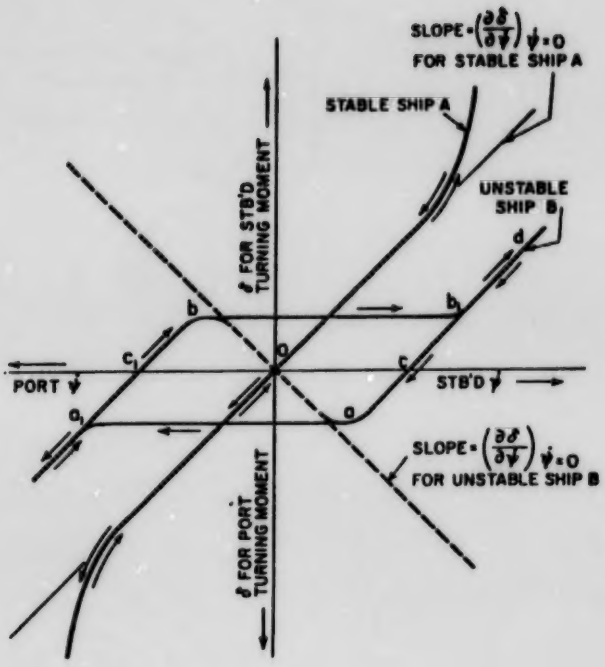

FIG.4.1.2a - Schematic Form of Spiral Manoeuvre

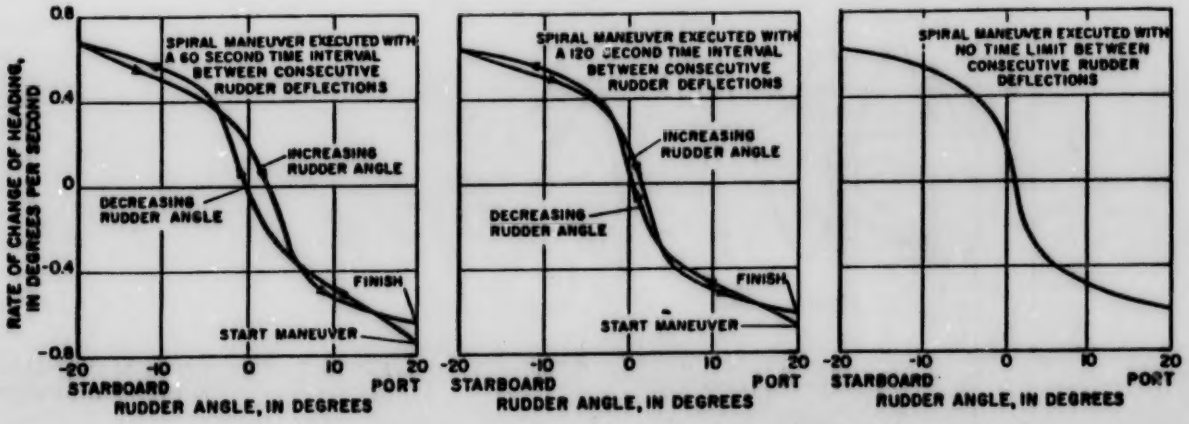
SPIRAL MANEUVER EXECUTED WITH A 60 SECOND TIME INTERVAL BETWEEN CONSECUTIVE RUDDER DEFLECTIONS
INCREASING RUDDER ANGLE
DECREASING RUDDER ANGLE
FINISH
START MANEUVER
RATE OF CHANGE OF HEADING, IN DEGREES PER SECOND
STARBOARD
PORT
RUDDER ANGLE, IN DEGREES
SPIRAL MANEUVER EXECUTED WITH A 120 SECOND TIME INTERVAL BETWEEN CONSECUTIVE RUDDER DEFLECTIONS
SPIRAL MANEUVER EXECUTED WITH NO TIME LIMIT BETWEEN CONSECUTIVE RUDDER DEFLECTIONS

FIG.4.1.2b - Typical Results of Spiral Manoeuvre

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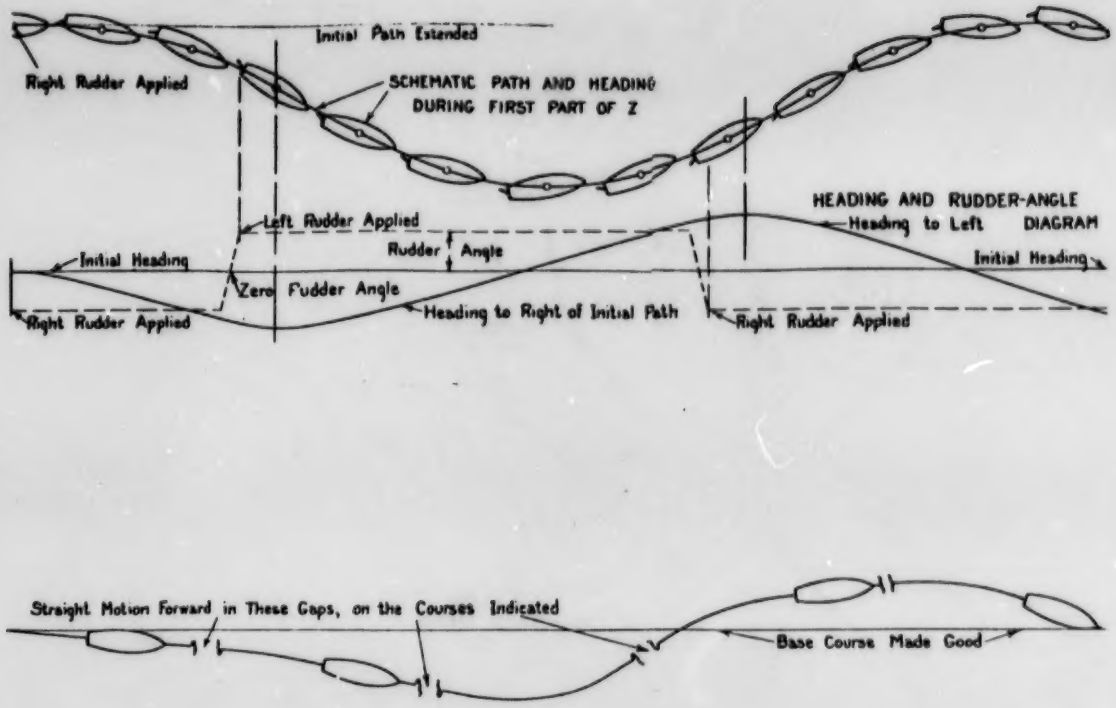
Initial Path Extended
Right Rudder Applied
SCHEMATIC PATH AND HEADING DURING FIRST PART OF Z
HEADING AND RUDDER-ANGLE DIAGRAM
Left Rudder Applied
Heading to Left
Rudder Angle
Initial Heading
Initial Heading
Zero Rudder Angle
Right Rudder Applied
Heading to Right of Initial Path
Right Rudder Applied
Straight Motion Forward in These Gaps, on the Courses Indicated
Base Course Made Good

FIG.4.1.3a - Schematic Form of Kempf Manoeuvre

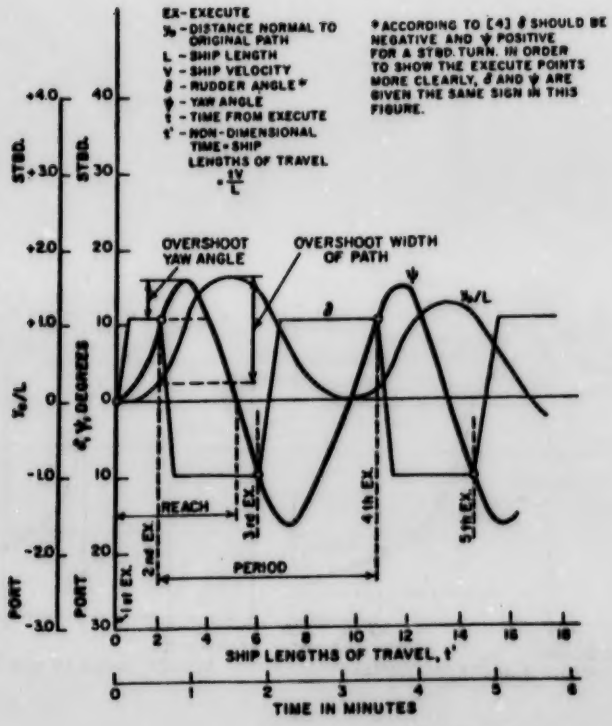
EX - EXECUTE
y_b - DISTANCE NORMAL TO ORIGINAL PATH
L - SHIP LENGTH
V - SHIP VELOCITY
δ - RUDDER ANGLE*
ψ - YAW ANGLE
t - TIME FROM EXECUTE
t' - NON-DIMENSIONAL TIME = SHIP LENGTHS OF TRAVEL = tV/L
*ACCORDING TO [4] δ SHOULD BE NEGATIVE AND ψ POSITIVE FOR A STBD. TURN. IN ORDER TO SHOW THE EXECUTE POINTS MORE CLEARLY, δ AND ψ ARE GIVEN THE SAME SIGN IN THIS FIGURE.
OVERSHOOT YAW ANGLE
OVERSHOOT WIDTH OF PATH
REACH
PERIOD
1st EX.
2nd EX.
3rd EX.
4th EX.
5th EX.
STBD.
PORT
SHIP LENGTHS OF TRAVEL, t'
TIME IN MINUTES

FIG.4.1.3b - Typical Results of Kempf Manoeuvre

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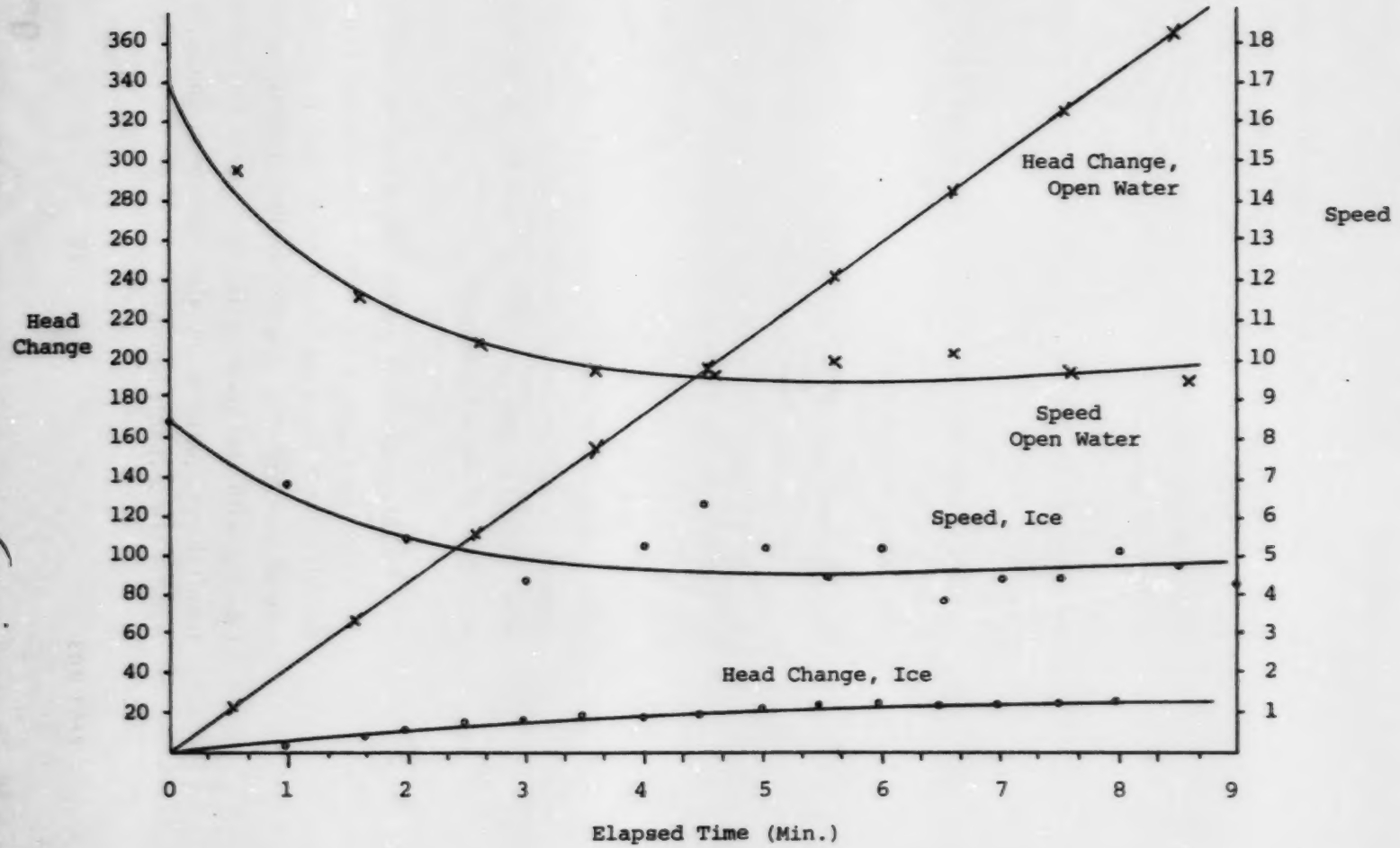
Figure 4.1.4

M.V. ARCTIC

Open water turning performance
22/1/80 full speed, 35° stbd. rudder
In-ice turning performance 20/1/80
full power, 35° port rudder.



all these to characteristic crack length or cusp size in the ice field being transitted.

Another notable feature of turns in ice is the existence of an additional phase. In open water the ships previous track has only a minor influence on the later stages of a turning circle, but in ice the existence of a broken channel is very significant. As the ships head turns back towards this channel in the third quadrant of the turn, ahead resistance and turning resistance will vary both absolutely and in relation to each other. The effects shows up in the speed and turning rate records, and in the radar traces of the ship's track, Figures 4.1.5 and 4.1.6.

Behaviour in the third and fourth quadrants is, however, of more theoretical than practical concern. The aspects of a turn of interest to an operator are likely to be:

- Advance in a 90° turn.
- Advance and transfer in a course reversal/180° turn.
- Duration and characteristics of the initial transient phase.
- Mean turning rate in the steady phase.

He will wish to know what the values for these are likely to be in a given operating environment, and also the extent to which he can control them by changes to power, rudder angle, or otherwise. The analysis in the later stages of this project will address all of these points, within the limitations of the available data.

Initial results show qualitatively a number of effects, some of which are illustrated by Figure 4.1.7, which superimposes three turning circles (one partial) recorded in open water and 18 and 32 cm of ice respectively. The rate of turn per ship length travelled reduces as ice thickness increased. Coupled with the lower sustainable speeds this increased considerably the time taken to perform any given change of course, while the advance and transfer are obviously increased.

Figure 4.1.5 - Turn at Baffin Island, 26/10/81
Ice Thickness 18 cm, full power

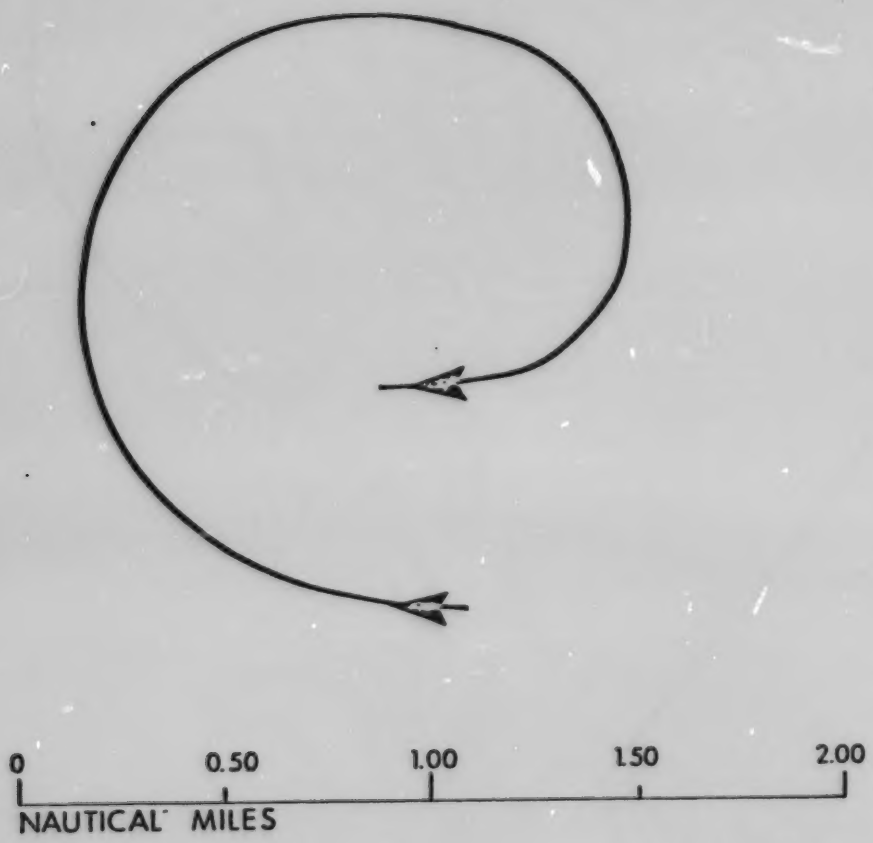
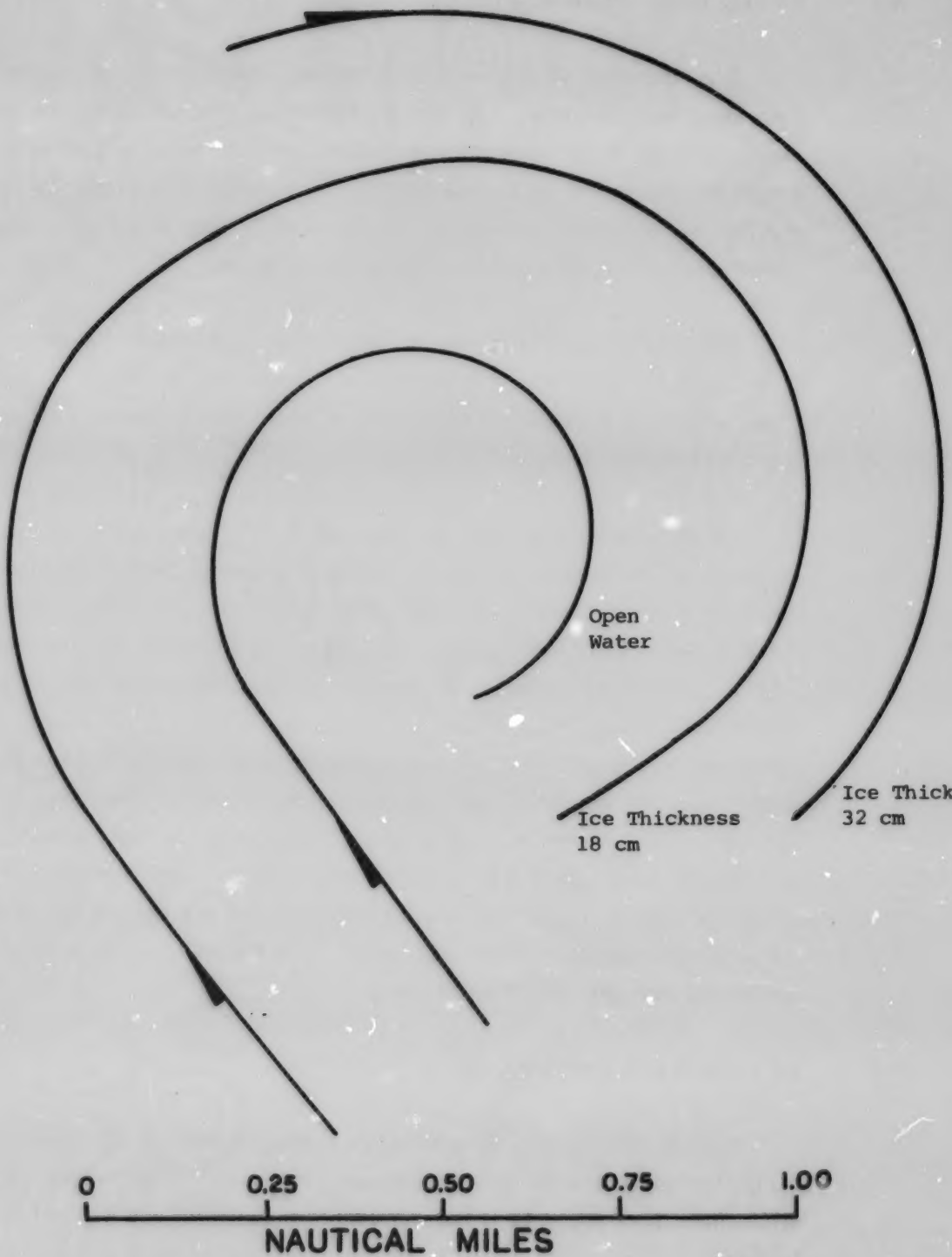


Figure 4.1.6 - Turn at Baffin Island, 31/10/80
Ice Thickness 33 cm, bubbler on,
full power



Comparison of Turning Paths in Various
Ice Thicknesses

Figure 4.1.7

4.0 M.V. ARCTIC MANOEUVRING PERFORMANCE ANALYSIS (Cont'd)

4.1 Turning Performance (Cont'd)

The duration of the transient phase also appears to reduce with increasing ice thickness. This can be explained by considering the smaller kinetic energy of the slower-moving ship, and the larger set of resistance forces present in ice, which will lead to a new equilibrium more rapidly than in open water. Short transients can be used to help to justify adopting a linear approach to most manoeuvring problems in ice.

There will obviously be a dependency on rudder angle for all characteristics of a turn. It is hoped that the full analysis of the records will yield sufficient information to support a hypothetical model explaining the form of this dependency.

Other manoeuvring options also exist with the M.V. Arctic. The influence of the bubbler system is discussed in Section 4.6. The effects of adopting a steady heel angle in the desired direction of turn have been investigated in Lake Melville, and a dramatic tightening of the turn reported / 19 /. The same effect has been noted in trials with the CANMAR KIGORIAK, though not explained. Several contributory influences can be identified amongst them a turning couple between the line of thrust of the shaft(s) and the centre of forward resistance. There is also likely to be a hydrodynamic lift force and moment generated by the asymmetrical underwater shape directed towards the centre of the turn. Probably of more importance, however, is that heeling the ship will present a more efficient icebreaking shape along much of the length of the hull, and thus reduce the forces and moments opposed to turning.

4.2 Ice Impacts with Steering Gear

Rudder stock strain data has been extracted for the 1981 season, that being the only one available. It has not been analysed at present. Rudder differential pressure data is not considered meaningful and will not be used further.

4.0 M.V. ARCTIC MANOEUVRING PERFORMANCE ANALYSIS (Cont'd)

4.3 Directional Stability

In conventional open water operation, the directional stability of a vessel can be given a measure by utilizing the controls fixed stability indices. These indices, which may be expressed in terms of the vessels force and moment derivatives, identify those forms which, with controls (i.e. rudder) fixed would, under a small perturbation to their motion, tend to continue to deviate from their path, and those whose response to the perturation will gradually damp out and which would then return to a steady course.

From / 2 / the criterion for controls-fixed stability in straight line motion can be expressed as:

$$Y'_v (N'_r - m'x'_g) - (Y'_r - m')N'_v > 0$$

From the calculated values of the motion derivatives (see Section 2.2), it is seen that N'_r, Y'_v and N'_v are all negative. With the origin at G, $x'_g = 0$ so the value of the expression above is about +.01. This implies directional stability for the M.V. Arctic in open water and is in line with reported values for broadly similar ships / 2 /.

In theory, similar stability indices could be obtained for operation in ice also, if the corresponding force and moment derivatives could be obtained. This requires either a theoretical model or physical investigations. Model Planar Motion Mechanism tests have sometimes been performed for some designs, although such data is unavailable for the M.V. Arctic. It is also conceivable that with sufficient data covering sway and yaw velocities and accelerations and full information concerning vessel mass distribution that a suitable regression analysis could be performed that would yield values for these derivatives. However, these data available for the M.V. Arctic are incomplete, limited in range and not believed to be always reliable. Further discussion on rigid body motions may be found in section 4.7 of this interim report and the question of values for motion derivatives is expanded in section 5.2.

4.0 M.V. ARCTIC MANOEUVRING PERFORMANCE ANALYSIS (Cont'd)

4.3 Directional Stability (Cont'd)

In actual operation in ice, experience has shown that the non-homogeneity of the ice leads to frequent perturbations. Experience also indicates that vessels in ice tend to resist changes in heading. This characteristic plus the frequent and random nature of disturbances in ice indicates that conventional representation of directional stability is of little value to the operator. Of greater importance is the facility with which a selected heading can be maintained under various ice conditions encountered.

This can be described in terms of the rapidity with which the vessel responds to commands, as well as the frequency and magnitude of those commands. It can be appreciated that these measures, particularly the latter, are partly dependent on the wheelhouse team at a given time. However, since this study is concerned with one vessel and most of the data was obtained in a few sessions covering a day or two, the variation in quality of the wheelhouse team is considered to be minor.

The data examined for straight ahead motion stability in ice comprised of runs recorded during dedicated trials in the three seasons of operation. Table 4.3.1 summarizes the principal elements and gives an overall indication of the range and quality of the data.

It appears, from Table 4.3.1 and also from Figures 4.3.1 and 4.3.2 that for the range of operating conditions, the vessel heading can be maintained quite accurately (within $\pm 2°$) most of the time. Test D22 which shows an 8° variation is apparently in an early phase of the test before a suitable heading was established, as it appears from D22b which immediately follows in time.

Also indicated from these data is that variation of heading increases with increasing ice thickness. Test D1 in the thickest ice was also at a substantially lower speed than the other tests, and this too may have an influence on heading variation.

TABLE 4.3.1

Heading and Helm Variations in Various Ice Conditions

Test Start Time	Elapsed Time (Secs)	Heading Range About Mean	Rudder Angle About Mean	(Uncorr) Ship Speed (avg.) Kts	Power kW / Thrust KN	Wind Kts	Ice Thick cm	Ice Type. op. Mode	Remarks
D1 (81/3/1/12/11/0)	450	±1.5°	±15	3	10,500/8500 920/780	0-8	80-110	New. Cont.	Rudder commands v. busy. Heading variation principally ±0.5°. Bubbler on part time.
D5 (80/10/26/12/23/57)	130	±0.5°	±3°	12	n.a. 770	16	18-18.6	New. Cont.	Wind given as 3-4 KTS in M.D.P.
D13 (80/10/28/15/55/0)	290	±1°	±8°	10	n.a. 500	30	29	Broken. Cont.	
D14 (80/10/29/16/8/36)	-	-	-	-	-	-	-	-	Bad Data
D16 (80/10/30/12/50/16)	210	±0.5°	±8°	9	n.a.	16	5-20	New. Cont.	Voyage monitoring condition. Bubbler on.
D22 (80/1/20/8/4/1)	420	±8°	±18°	10	n.a. 700	55	44.5	New. Cont.	I.B. support. Large mean rudder. (Due to wind?)
D22 b(80/1/20/8/17/1)	170	±2°	±20°	11	n.a. 750	55	44.5	New. Cont.	Rudder response follows commands poorly.

TABLE 4.3.2

Number and Type of Helm Actions in Various Ice Conditions

Test	Elapsed Time Sec.	No. of Rudder Actions	Actions/ Min.	No. of Zero crossings (abt mean) Distinct Acts	Distinct Action /Min.	Rate of change of Heading $d\Psi/dt$ 0/Sec.	δ (from Mean)	$K = (d\Psi/dt)/\delta$	Approx. Mean Helm
D1	450	70	9.3	28	3.7	.1	9°	.011	0
D5	130	16	7.4	8	3.7				2
D13	290	20	34.1	6	1.2				0
D14	-	-	-	-	-	-	-	-	-
D16	210	29	8.3	16	4.6	.033	5	.007	5
D22	420	2.3	3.3	8	1.1	.083	6	.013	30°
D22b	170	14	4.9	7	2.5	.133	10	.013	30°

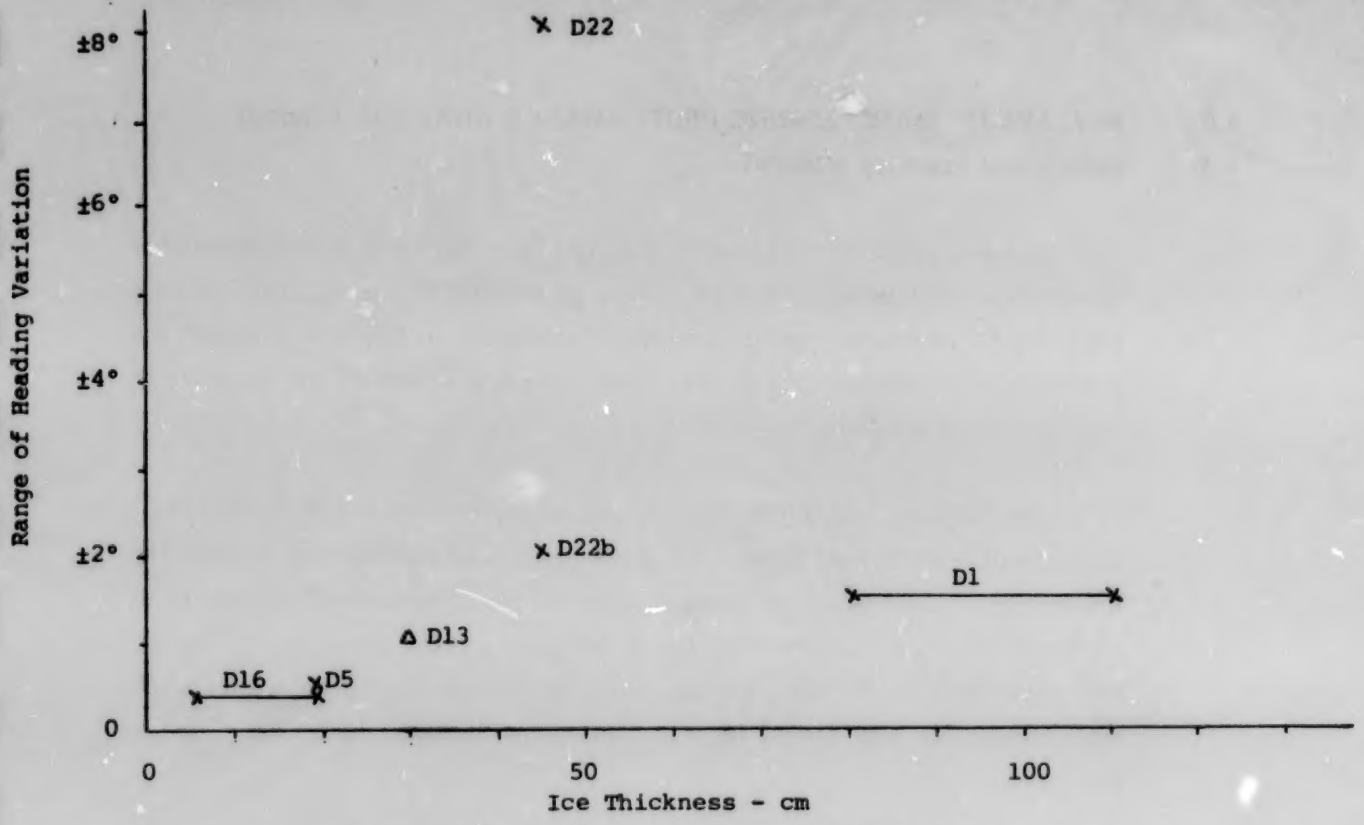


Figure 4.3.1 - Range of Heading Variations in Various Ice Thicknesses

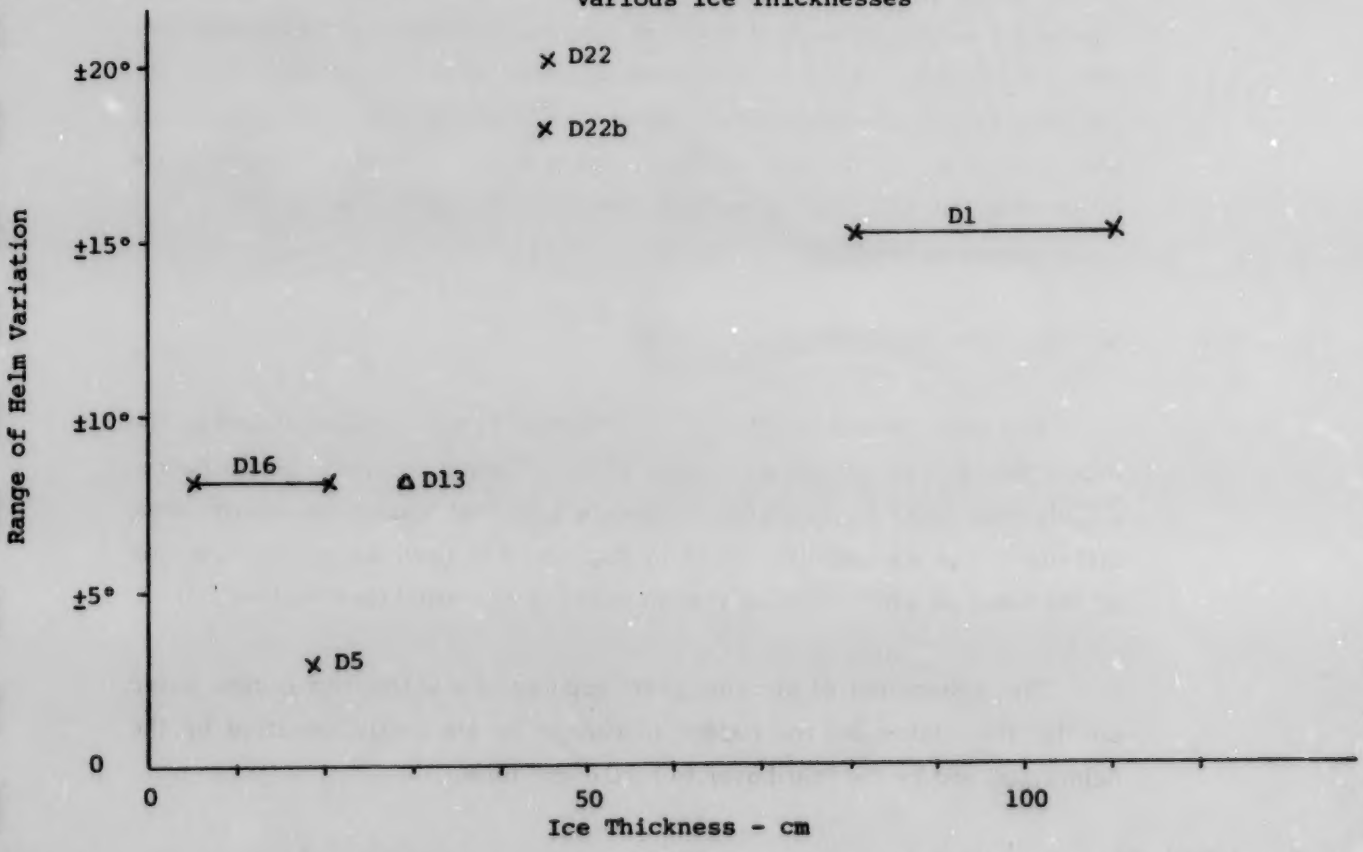


Figure 4.3.2 - Range of Heading Variations in Various Ice Thicknesses

4.3 Directional Stability (Cont'd)

Bubbler operation (D1 and D16) do not have any obvious influences, nor does operation in broken ice (D13). The high wind (in D22 and D22b) may be a cause of the somewhat poorer directional capability in this test, although the presence of icebreaker support may have had some effect on the integrity of the continuous ice field.

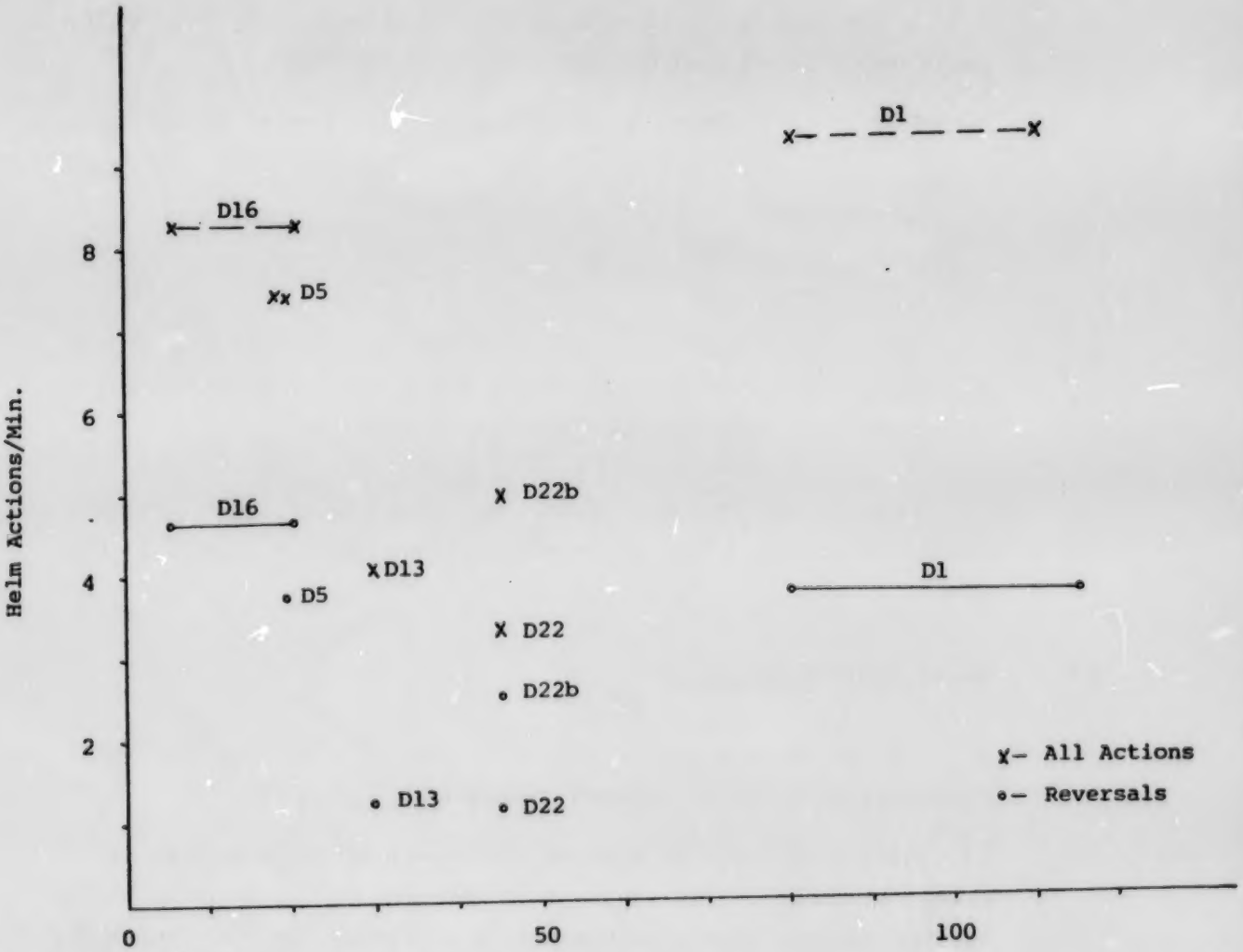
The facility with which heading can be maintained can be indicated by the rate of helm action Table 4.3.2 and Figure 4.3.3 show approximately the number of actions (distinct changes in helm) per minute and the number of reversals (distinct changes from the mean) per minute. Brief "twitching" of the helm has, as far as possible, been discounted. Still, there is some subjectivity, at this stage, in interpreting an "action" from the data as presented.

From Figure 4.3.3, it appears that ice thickness is not a particularly significant factor or at least that the amount of information available does not justify trying to fit an empirical equation to it. However, broken ice conditions seem to require a much lower rate of action. Test D22 in level ice also has a low action rate. However, this test also showed wider divergence in heading, so the reduced action rate may be the cause of the poorer maintenance of heading.

4.4 Steering Gear Response Characteristics

The celerity with which the rudder responds to commands issued by the helmsman is an important feature of steering system performance. Regulations exist that require a certain speed of rudder movement also, although these are usually related to ship speed in open water and form one of the bases on which steering system power is computed (See Section 5.3).

The assessment of steering gear response characteristics is thus based on the time taken by the rudder to change by the angle specified by the helmsman, and by the "hard over to hard over" time.



Ice Thickness - cm

Figure 4.3.3

Helm Actions in Various Ice Thicknesses

4.0 M.V. ARCTIC MANOEUVRING PERFORMANCE ANALYSIS (Cont'd)

4.4 Steering Gear Response Characteristics (Cont'd)

At this stage, a visual assessment of the data records indicates that the rudder response tracks commands very closely for example:

Test	Helm Change Commanded	Time to Achieve
D4(81/3/3)	35°	12 - 15 sec.
D2 (81/3/1)	10	5 sec.
D2 (81/3/1)	20	10 sec.

An overlay of rudder command and rudder response data for a typical test (D1) in Figure 4.4.1 shows the close correspondence obtained. This type of correspondence is apparent in nearly all data examined.

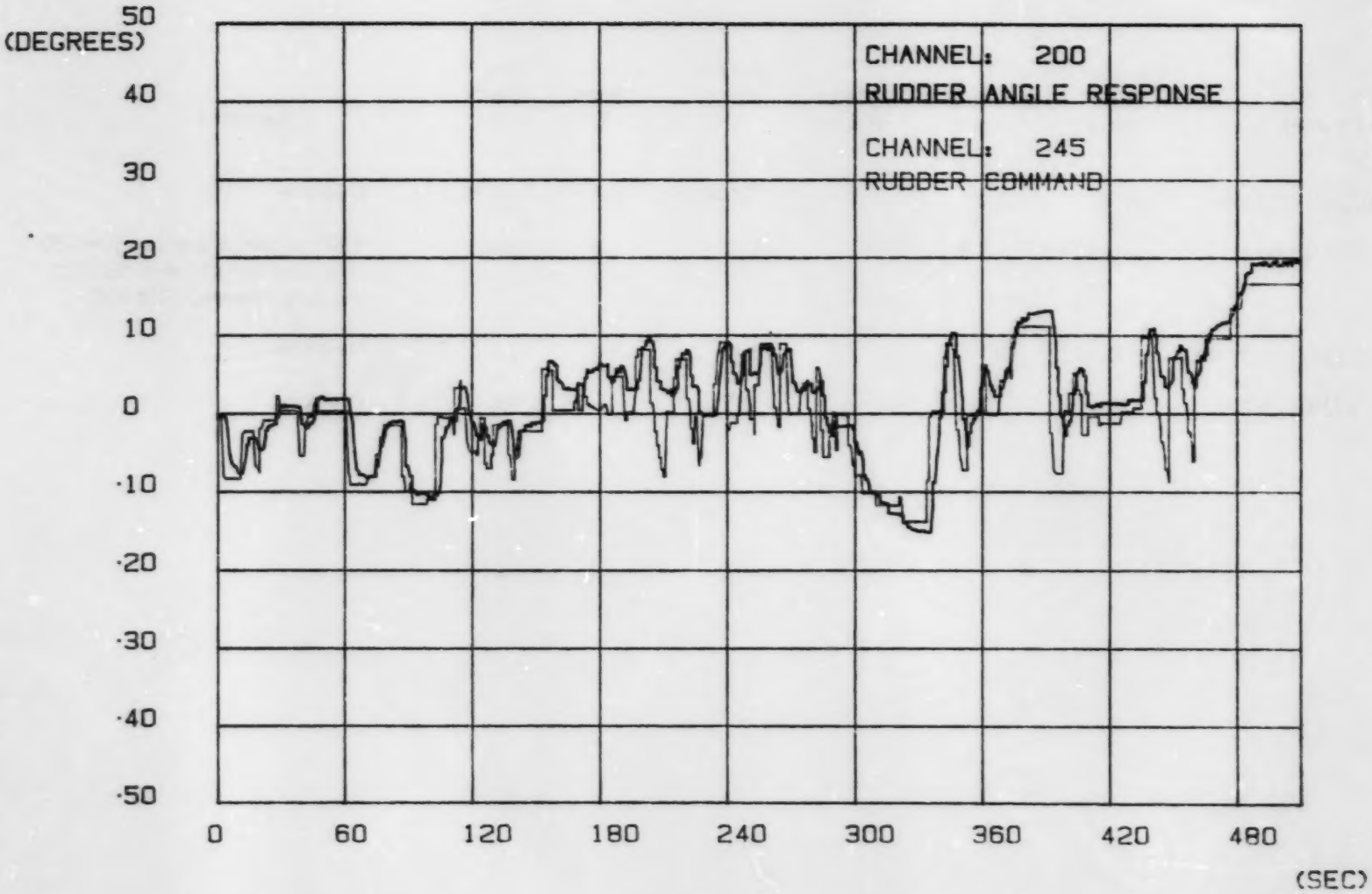
Tests D5 and D22b show distinct anomalies such as rudder commands followed by delayed or inconsistent responses. No reason is apparent at this time.

4.5 Astern Performance

The dedicated trials involved only a few tests of astern operation. These were during the Baffin Island Trials of 1980.

The quality looked for in astern performance in ice is principally one of directional stability. This is to avoid the necessity of utilizing the rudder to maintain direction, thereby putting it at risk of damage due to ice impact. A second factor of importance in astern motion is that of rudder stock torques and impact forces due to astern motion. This subject is discussed in section 4.2 of this interim report.

Table 4.5.1 summarizes the main data elements. They indicate that for the limited range of ice conditions recorded, the vessel maintains its path with ease. This is possibly due to the fact that it is probably backing into a channel of its own creation. This is also the probable cause of the absence of change in heading (Test D8) even when 30° of rudder is applied for some 3 minutes.



START: 81 / 3 / 1 / 12 / 11 / 0 FIGURE: 4.4.1

Rudder Command vs Response

TABLE 4.5.1

Astern Motion

Test (Start Time)	Elapsed Time (Sec.)	Heading Range	Helm Range	Astern Thrust kN	Wind Kt	Ice Thick cm	Remarks
D7 (80/10/29/10/2/39)	840	±1.5°	0	220-400	0-8	20-26.7	New Ice
D8 (80/10/27/15/4/21)	660	±1.5°	*	400	6-8	n.a.	*30° of Helm applied for ~90 secs. did not cause a distinct heading change. Old ice.
D7 b(80/10/27/10/17/30)	300	±2°	0	250	4-6	20-26.7	New ice.
D21 (80/10/29/9/5/22)	280	0	0	135	12-25	43	Old ice.

4.0 M.V. ARCTIC MANOEUVRING PERFORMANCE ANALYSIS (Cont'd)

4.6 Influence of the Installed Bubbler System; Alternatives

The performance of the bubbler system will be the subject of further analysis in the later stages of this project. It does appear to offer considerable increases in rate of turn over a range of powers and ice thicknesses. In the open water case the bubbler can be used to generate side thrust by feeding air only to the side of the hull outboard to the turn. In ice the mechanism is completely different, in that it appears to be assisting turning by breaking the ice inboard.

4.7 Rigid Body Motions

The motion of the vessel in the horizontal plane involves surge, sway and yaw. The influence of surge in this study of manoeuvring is believed to be minimal. However, roll is deemed to be of some significance. For this reason, the data examined consisted of the fore and aft sway accelerometers and the roll indicator.

The fore and aft sway readings are converted to sway and yaw at midships based on the positioning of the transducers.

The equations of motion in section 2.2 represent a balance between the inertial and hydrodynamic forces on the vessel. If rudder action is introduced, then an additional set of forces and moments must be accounted for, and the equations may be rewritten as:

$$-Y'_{\dot{v}}v' + (m'-Y'_{v})v - (Y'_{\dot{r}}-m')r' - (Y'_{\dot{r}}-m'x_{g'})r' = Y'_{\delta}\delta$$

$$-N'_{\dot{v}}v' - (N'_{\dot{v}}-m'x'_{G})v' - (N'_{\dot{r}}-m'x'_{G})r' - (I'_{z}-N'_{\dot{r}})r' = N'_{\delta}\delta$$

The right hand side of these equations represents the sway force and yaw moment acting on the vessel as a result of applying a rudder angle δ.

4.7 Rigid Body Motions (Cont'd)

Since the force/moment derivatives for the vessel in ice have not been obtained by model tests, it is conceivable that they may be approximated using regression techniques and data on sway and yaw accelerations and velocities.

Sway and yaw velocities not being measured, an attempt has been made by integrating the acceleration records. The accelerations, however, indicate significant (and inconsistent) offset, part of which is, of course due to some initial velocity, but part is also due to electronic offset generated in the recording system.

By examining straight ahead runs where there was little heading change, and the average sway acceleration could be expected to be around zero, attempts were made to adjust for this offset. In most instances, it was found that the yaw acceleration computed out to near zero as was to be expected. However, the sway acceleration showed much variation, so much so that the velocity values resulting from integration were of considerable magnitude. Arbitrary corrections for the offset does change the velocities, but consistence could not be obtained for different tests. Also it appeared that the offset may be drifting during the test run, making adjustments or corrections too subjective to be useful for analysis.

For example, test D16 (see Appendix B) indicates sway velocities upto 40 m/s. By adjusting the offset, this can be reduced to around $\pm$15 m/s. This is about 3 times the ahead velocity. Sway displacements from the velocity figures are approximated at around $\pm$ 200 - 250 m in this case. Actual sway displacements can be expected to be around about cusp depth values, which in ice of about 5-20 cm would be of the order of less than 1 m.

The lack of good data from the important sensors would make additional work on the analysis of rigid body motions of little likely benefit. It is, therefore, not intended to pursue this topic further.

5.0 MANOEUVRABILITY AND CONTROL IN ICE

5.1 General

From the analysis discussed above, it can be seen that there are considerable differences between the manoeuvring problems encountered in open water and those in ice. Some of the reasons for this have been noted already, and will be expanded on in the final project report. The discussion in the following sections is intended to indicate the overview of the subject within which future analysis will be carried out.

5.2 The Manoeuvring Environment

In order to turn, a ship has to adopt a drift angle while maintaining forward motion. In open water, applying a rudder angle will generate a turning moment, which will at the equilibrium drift angle be balanced by the hydrodynamic forces and moments associated with that angle and rate of turn. This is the situation described by the equations of motion quoted in Section 2.2, which again using a simplified linear representation of a steady turning condition can be used to yield:

$$\frac{R}{L} = \frac{1}{6} \; Y'_v \; \frac{(N'r - m'x'_G) - N'_v(Y'_r - m')}{Y'_v N' \; - N'_v Y'}$$

This has been found to give good estimates of steady turning radii for values of R/L = 8-10.

All the hydrodynamic derivatives, Y'_v, N'_r, etc. for open water could be assumed to have in-ice equivalents, and it can be proposed that, for example:

$$N'_{v\,\text{total}} = N'_{vo} + N'_{vi}$$

the subscripts referring to open water and ice-related components. As indicated in 4.1, however, the ice components will be average figures, as the process of transitting through ice in any fashion is discontinuous. A second major difference is that even these average values will not vary smoothly with sway velocity, yaw rate etc., as is the case in open water. Thirdly, ice

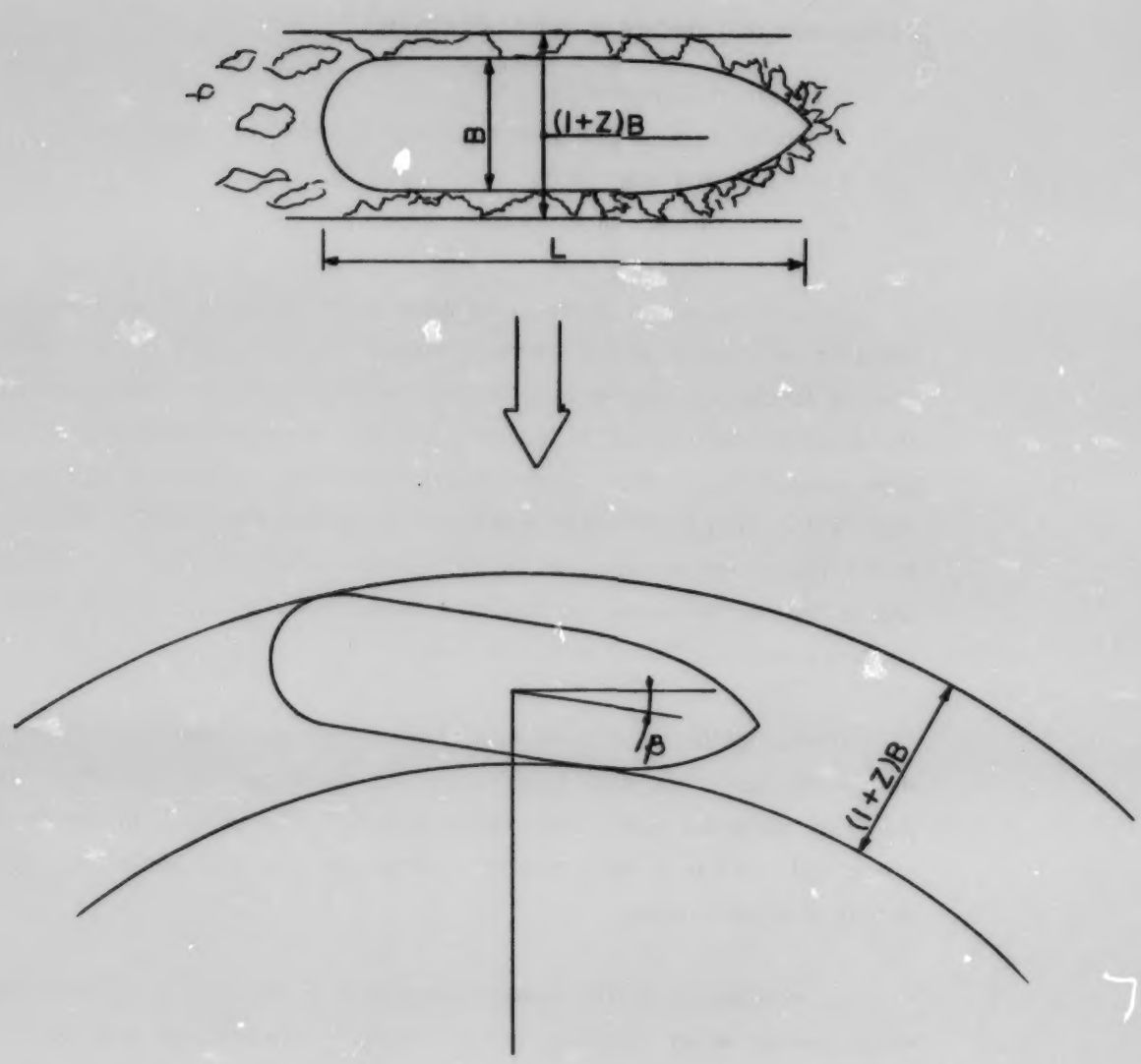
coefficients will vary with the characteristics and thickness of the ice.

The variation of the coefficients with sway and yaw will procede in several phases. When a ship advances though an ice field, it breaks a path whose width is related to the bow geometry of the vessel and to the ice properties. If the ship then initiates a turn, at small angles the path swept by the angled hull will be entirely within this broken path as shown by Figure 5.2. The forces and moments opposing the turn will, therefore, be due to displacing broken fragements.

At a critical turning rate, the sides of the ship will be required to start breaking additional ice. Its ability to do this will be related to the turning force which the rudders can exert, and also to the efficiency of the ship side in icebreaking. For all vessels, in ice above a certain thickness, it will be impossible to exceed the critical turning rate, and there will be no point in attempting to do so while squandering potential ahead thrust in the attempt.

If the ice is sufficiently thin for the ship to exceed the critical rate, there will be a step jump in resistance to turning to the value required to initiate breaking, followed by a rise proportional to the rate of icebreaking and ice displacement.

Examining the subject in this way has already suggested a number of ways of interpreting existing data and various avenues for future investigation. For example, the crucial importance of L/B ratio has been noted in earlier studies e.g. Ref. / 10 / and can be explained in terms of these mechanisms. In the same reference, the influence of high values of C_B in reducing manoeuvrability was described. This probably has more to do with the more vertical ship sides required to achieve large C_Bs than with any other characteristic of a high C_B form, and it may be possible to use flare over localized portions of the fore and after bodies to remove most of the disadvantages.



The 'Critical Turn' in Ice

Figure 5.2

5.0 MANOEUVRABILITY AND CONTROL IN ICE (Cont'd)

5.3 CASPP Regulations - Ship; and Steering Gear Systems

The latest version of the provisions of the Canadian Arctic Shipping Pollution Prevention Regulations relating to the selection of steering arrangements, and the original requirements, are presented in Appendix A. It can be seen that the areas addressed cover:

- Strength of components.
- Power of internal machinery (through speed of response).
- Configuration externally.
- Provision of back-up and safety measures.

Before discussion of the provisions which do exist, it is instructive to consider an area in which no requirements are specified, i.e. the potential turning forces and moments from the rudder. Two basic quantities govern the available turning force; flow velocity over the rudder and rudder size. In open water a rudder will almost always experience a flow velocity similar to that of the ship, modified by wake effects and by the propeller slipstreams. In ice there may on occasion be only a very small forward velocity, so to ensure that an adequate turning force remains available, it is important that rudders are placed in the propeller race.

The propeller race itself will have velocity and extent dependent on the design of the propulsion system, and in particular on the shaft speed, propeller diameter and power characteristics. In general, higher installed power will lead to a more energetic propeller race and hence to a greater potential turning force.

A possible trap for unwary designers is to ignore manoeuvrability requirements when choosing power levels. Some newer hull forms are particularly efficient icebreakers which leave a broken track little wider than their beam. As described in Section 5.2, this means that they will also have a low critical rate of turn. If their low ahead resistance has led to a small installed power, such ships will be unmanoeuvrable in relatively small ice thicknesses. Increasing the size of rudder could be a palliative in these cases, but has numerous strength and vulnerablity implications.

5.0 MANOEUVRABILITY AND CONTROL IN ICE (Cont'd)

5.3 CASPP Regulations - Ship and Steering Gear Systems (Cont'd)

The evolution of the strength requirements shown in Appendix A has discarded an original standard which bore little relation to likely ice loads, but now provides no useful guidance to designers, calling for strengthening "as necessary to withstand the anticipated loading". The question of what an anticipated loading might be will be expanded in the final report, but at present it appears possible that a worst combination of fragment size and relative velocity could be developed by considering the characteristics of a ship's turning path in a range of ice conditions, and this used as a design condition for ahead motion. The choice of a suitable design loading for astern motion is equally or more important, but has to be tied in with operating procedures.

Classification societies in general, specify minimum rudder response rates, which are traditionally regarded as acceptable rather than being based on analytical investigation. The CASPP Regulations have followed this approach. A comparison between CASPPR and Lloyd's Rules is:

CASPPR : The main steering gear ... shall be capable of moving the rudder from 35 degrees on one side to 30 degrees on the other in

$$2.56\sqrt{L} \text{ seconds}$$

(L ship length in metres)

Lloyd's : The main steering gear shall be capable of (at full speed) ... putting rudder from 35° on either side to 30° on the other side in not more than 28 seconds.

As no ship speed is specified in CASPPR, it is assumed that this rate of response should be available at all speeds. There appears to be little reason for rates of response in ice to be necessarily more rapid than those in open water, as in general the response of the ship will be much slower. This requirement will, however, be imposed on design based on Lloyds and similar rules by CASPPR for ships of less than 120 m length (therefore, excluding the

M.V. Arctic). Increasing system power to give rapid response may on the other hand make it more difficult to design shock-absorbing protection or provide back-up for the main steering gear.

The CASPP steering gear regulations will be more fully discussed in the final project report.

6.0 EVALUATION OF DATA ACQUISITION SYSTEM

There are basically two aspects of the data acquisition system that are of concern in analyses of this sort.

The first, which concerns the physical system, deals with the type, suitability, reliability, etc. of the various sensors, associated signal amplifiers/conditioners, and the recorders and data storage system. At this stage of the study, it appears that many of the difficulties encountered with this part of the system have, over the three operating seasons, been gradually resolved. However, certain sensors, notably those for the rudder differential pressure and for the RPM have received very little attention although neither is meant to measure any unusual characteristic or to be of especially unpredictable magnitude.

The second aspect, which is believed to be of much greater significance, concerns the strategy and planning phase of any data acquisition system. This involves the initial decision making process when the properties or characteristics to be studied and analysed are determined and the physical states to be monitored are determined.

It is this latter more important aspect which appears to have received little attention, at least as far as monitoring manoeuvring capability is concerned. There does not appear to have been any initial plan as to which specific characteristics of manoeuvring were to be measured, except perhaps for turning circle diameter.

The absense of a master test plan resulted in tests where some variables of importance were not measured at all. This also led to tests being conducted in a haphazard manner and at times when a complete test team was not standing by.

The final report will suggest procedures for planning and testing that should help in yielding more useful and complete information in future manoeuvring trials. However, a few of the principal points to be considered are shown here.

6.0 EVALUATION OF DATA ACQUISITION SYSTEM (Cont'd)

a) Two or more means of measuring a variable should be available, and preferably of different type. This will allow cross checking as well as redundancy.

b) Outline analysis procedure beforehand so all relevant sensors can be monitored.

c) Check and calibrate sensors regularly and prior to test.

d) Standardise data identification system so different investigators can utilize and comprehend a common data base.

e) Record all relevant data including manually derived or estimated values in the common data base so all relevant information is stored in one place.

f) Estimate expected range of values before testing so sensor data may be examined critically during and immediately after testing.

7.0 RECOMMENDATIONS FOR FUTURE WORK

Recommendations will be based on the full analysis and assessments presented in the final report. It is probable that areas covered will include:

a) Expanding the data base, using the M.V. Arctic, other vessels, and model tests. It will be of particular interest to retest the 'Arctic' after the installation of the proposed new bow design. Future tasks and trials would take place using acquisition strategies and equipment incorporating lessons learnt from this project.

b) Performing further theoretical studies to identify and better qualify the importance of various parameters discussed in the project reports.

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9.0 LIST OF SYMBOLS

L	-	Ship length between perpendiculars
B	-	Ship (maximum) beam
T	-	Ship draught
C_B	-	Block coefficient
V	-	Ship forward velocity
v	-	sway velocity
r	-	yaw angular velocity $\equiv \dot{\psi}$
R	-	Steady turning radius
Y	-	Force acting perpendicular to ship centreline
N	-	Moment acting about vertical axis
Y'_v, N'_r, etc.	-	Dimensionless force, moment coefficients developed from partial derivatives with respect to v, r, etc.
X'_G	-	Dimensionless position of ship centre of gravity
m'	-	Dimensionless mass
δ	-	Rudder angle
β	-	Drift angle
ψ	-	Yaw angle
t	-	Time
t'	-	Dimensionless time , $\frac{tV}{L}$

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APPENDIX 'A'

CASPP Regulations for Steering Gear Design

APPENDIX 'A'

February, 1984

SCHEDULE VI

HULL DESIGN FOR ARCTIC CLASS SHIPS

Rudder and Steering Gear

11. (1) The rudder, rudders posts, rudder stocks, pintles and steering gear of every Arctic class ship shall be strengthened as necessary to withstand the anticipated loading that a ship of that Arctic Class may experience when navigating in those zones and at those times of year in which a ship of that Arctic Class is permitted to operate.

(2) The main steering gear of every Arctic Class ship shall be fitted with a shock absorbing device and shall be capable of moving the rudder from 35 degrees on one side to 30 degrees on the other in

$$2.56\sqrt{L} \text{ seconds}$$

where L is in metres

(3) Every Arctic class ship shall, in addition to the main steering gear, be fitted with

(a) an auxiliary steering gear capable of being readily connected to the tiller and, in the case of a ship of that category fitted with twin rudders operated by a single steering gear, an arrangement so that each rudder can be readily disconnected and secured; or

(b) an effective alternative means of steering the ship such as multiple propellers or side thrust arrangements.

(4) Every Arctic class ship shall be fitted with ice horns directly abaft each rudder in such a manner that

(a) the upper edge of the rudder is protected within two degrees port and starboard of mid-position when going astern; and

(b) ice is prevented from wedging between the top of the rudder and the ship's hull.

Extract from Chapter 353 - Schedule VI

(Revoked and substituted by SOR/78-180 February 1978)

Rudder and Steering Gear

11. (1) Subject to subsection (7), the rudders, rudder posts, rudder stocks, pintles and steering gear of every Arctic class ship shall comply with the *Hull Construction Regulations*.

(2) Subject to subsection (3), when calculations are being made for the strength of the rudders, rudder posts, rudder stocks, pintles and steering gear referred to in subsection (1), the speed of an Arctic class ship set out in Column I of an item of Table V shall be deemed to be the speed set out in Column II of that item.

(3) Where it can be shown that the maximum operating load on a rudder of a ship is greater than the load calculated by using the speed set out in Column II of an item of Table V for an Arctic class ship set out in Column I of that item, the rudder, rudder post, rudder stock, pintles and steering gear shall be designed for the higher load.

(4) The main steering gear of an Arctic class ship shall be fitted with a shock absorbing device and shall be capable of moving the rudder from 35 degrees on one side to 30 degrees on the other in

(*a*) $\frac{V}{21}$ seconds
where L is in feet; or

(*b*) $\frac{V}{6.56L}$ seconds
where L is in metres.

(5) Every Arctic class ship shall, in addition to a main steering gear, be fitted with an auxiliary steering gear capable of being readily connected to the tiller and, in the case of a ship with twin rudders operated by a single steering gear, shall be equipped so that each rudder can be readily disconnected and secured.

(6) Every Arctic class ship shall be fitted with ice horns directly abaft each rudder in such a manner that

(*a*) the upper edge of the rudder is protected within two degrees port and starboard of mid-position when going astern; and

(*b*) ice is prevented from wedging between the top of the rudder and the ship's hull.

(7) The rudder side plating for every Arctic class ship shall be reinforced for ice in direct proportion to the ice reinforcement required for the astern area plating.

Gouvernail et appareil à gouverner

11. (1) Sous réserve du paragraphe (7), le safran, les étambots, les mèches de gouvernail, les aiguillots et l'appareil à gouverner doivent être conformes aux prescriptions du *Règlement sur la construction des coques*.

(2) Sous réserve du paragraphe (3), dans le calcul de la résistance du safran, des étambots, des mèches de gouvernail, des aiguillots et de l'appareil à gouverner mentionnés au paragraphe (1), la vitesse d'un navire de cote arctique visé à l'un des articles du tableau V dans la colonne I est réputée être la vitesse indiquée dans la colonne II au même article.

(3) Lorsqu'il est possible de démontrer que la charge maximale d'exploitation sur le gouvernail d'un navire de cote arctique visé à l'un des articles du tableau V dans la colonne I est supérieure à la charge calculée d'après la vitesse donnée dans la colonne II au même article, le safran, les étambots, les mèches de gouvernail, les aiguillots et l'appareil à gouverner doivent être conçus pour résister à la charge supérieure.

(4) L'appareil à gouverner principal d'un navire de cote arctique doit être muni d'un dispositif amortisseur de choc et doit être capable de faire passer le safran de 35 degrés sur un bord à 30 degrés sur l'autre bord

a) en $\frac{V}{21}$ secondes
si L est exprimé en pieds; ou

b) en $\frac{V}{6.56L}$ secondes
si L est exprimé en mètres.

(5) Tout navire de cote arctique doit être équipé, en plus d'un appareil à gouverner principal, d'un appareil à gouverner auxiliaire qui peut être facilement accouplé à la barre et, dans le cas d'un navire à deux safrans commandés par un seul appareil à gouverner, d'un moyen de désaccoupler et d'immobiliser facilement chaque safran.

(6) Tout navire de cote arctique sera muni d'oreilles antiglace installées directement en arrière de chaque safran de façon à

a) protéger le bord supérieur du safran à deux degrés d'angle près à babord et à tribord de la position médiane pendant la marche arrière; et

b) à empêcher la glace de se coincer entre le haut du safran et la coque du navire.

(7) Les tôles de protection du safran de tout navire de cote arctique doivent être renforcées en proportion directe du renforcement qu'exige la navigation dans les glaces en fait de renforcement de la tôlerie de la section arrière.

TABLE V

Item	Column I Arctic Class	Column II Minimum Speed in Knots
1	1	16
2	1A	18
3	2	20
4	3	22
5	4	22
6	6	24
7	7	26
8	8	26
9	10	26

TABLEAU V

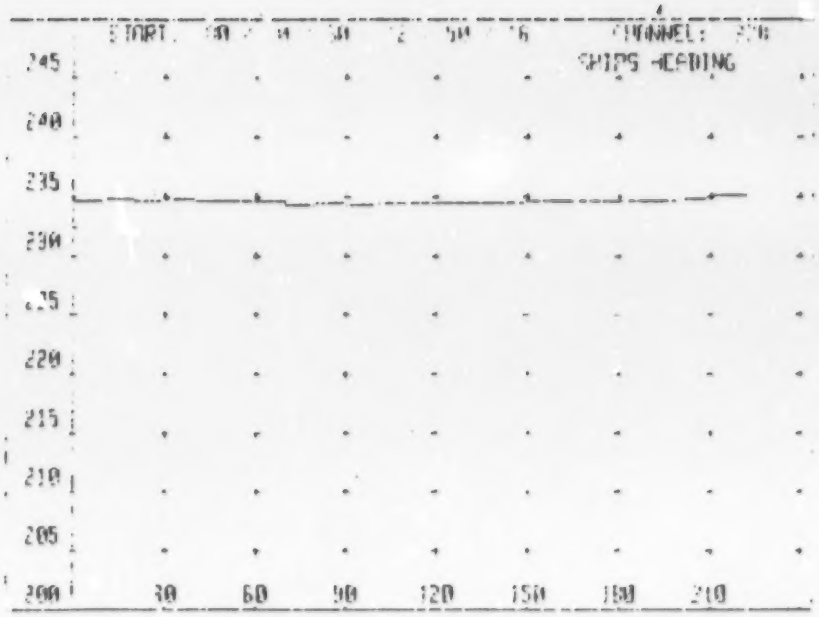
Article	Colonne I Cote arctique	Colonne II Vitesse minimale en nœuds
1	1	16
2	1A	18
3	2	20
4	3	22
5	4	22
6	6	24
7	7	26
8	8	26
9	10	26

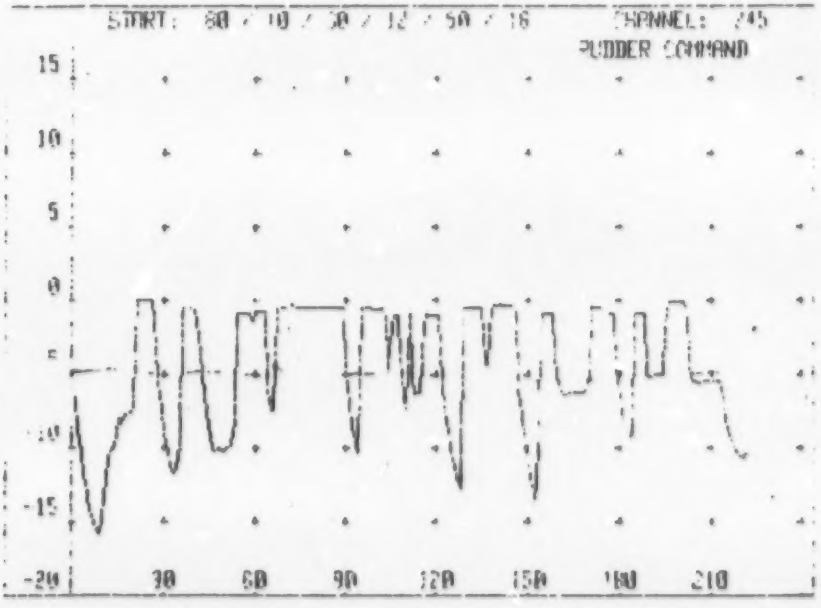
APPENDIX 'B'

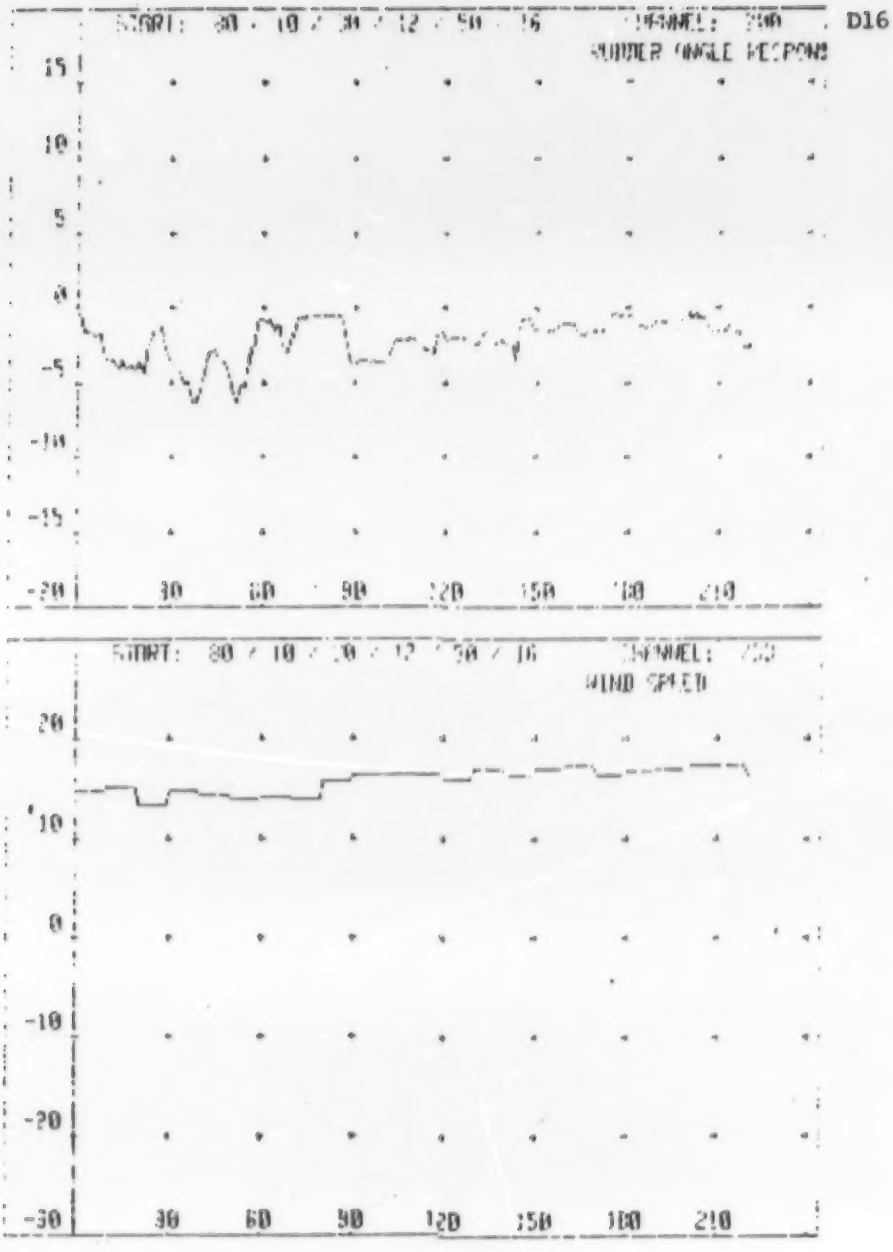
Sample Data Tape Printouts

APPENDIX 'B'

D16

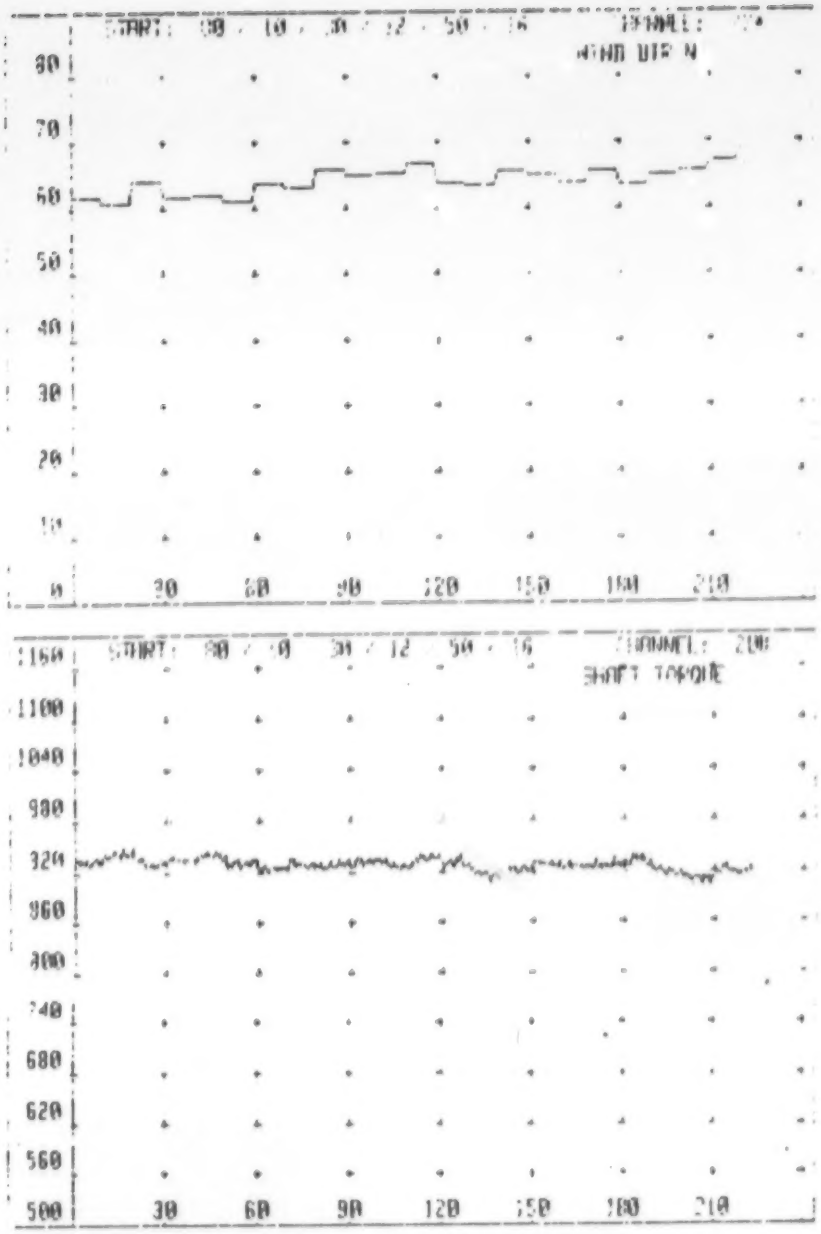




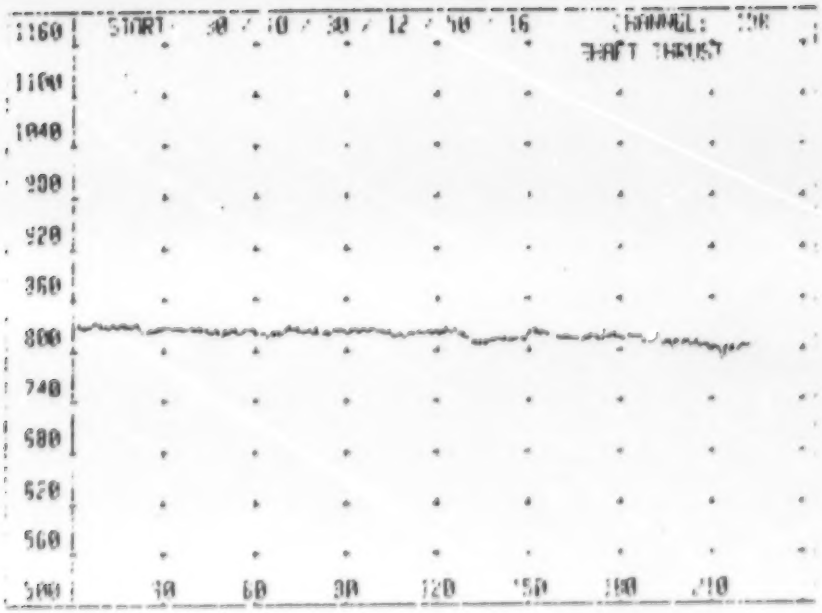

RUDDER ANGLE RESPONSE
15
10
5
0
-5
-10
-15
-20
30
60
90
120
150
180
210
WIND SPEED
20
10
0
-10
-20
-30
30
60
90
120
150
180
210

D16

D16


80
70
60
50
40
30
20
10
0
30
60
90
120
150
180
210
1160
1100
1040
980
920
860
800
740
680
620
560
500

D16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860
800
740
680
620
560
500
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180
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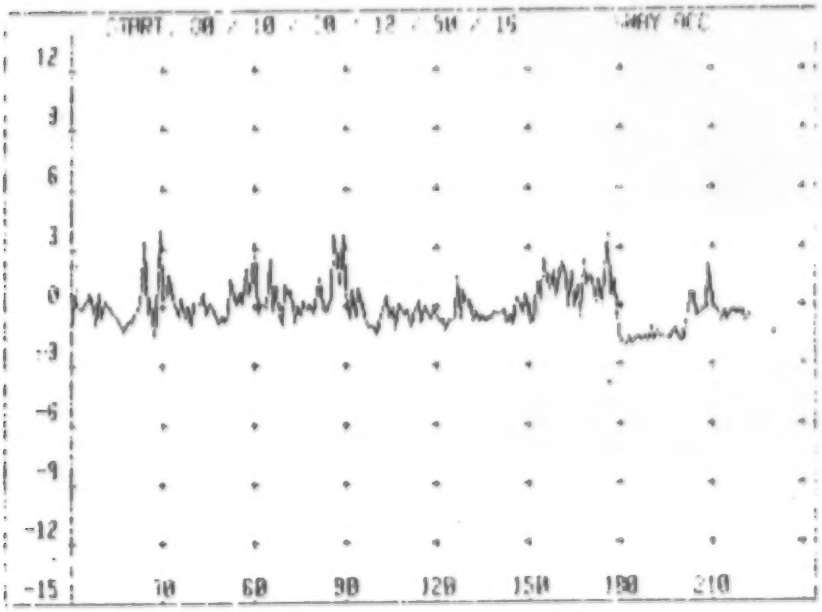
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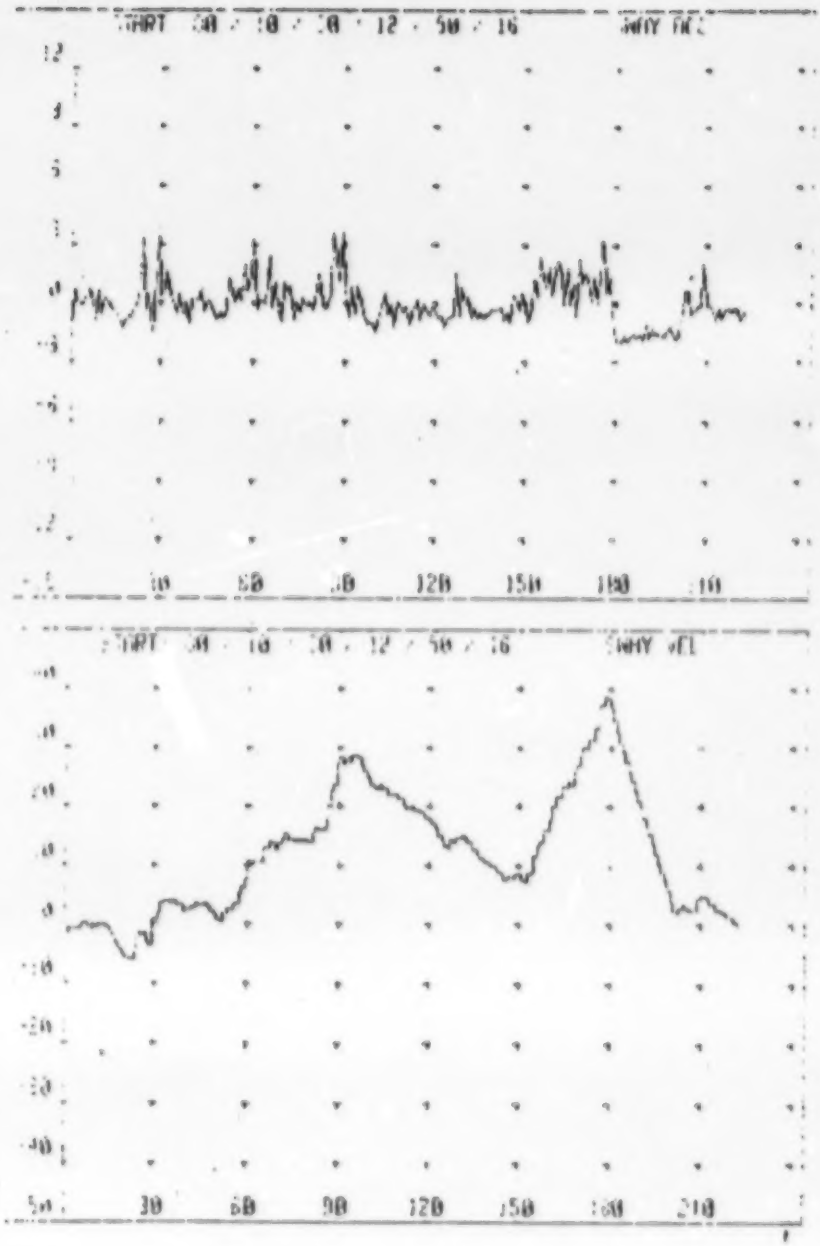
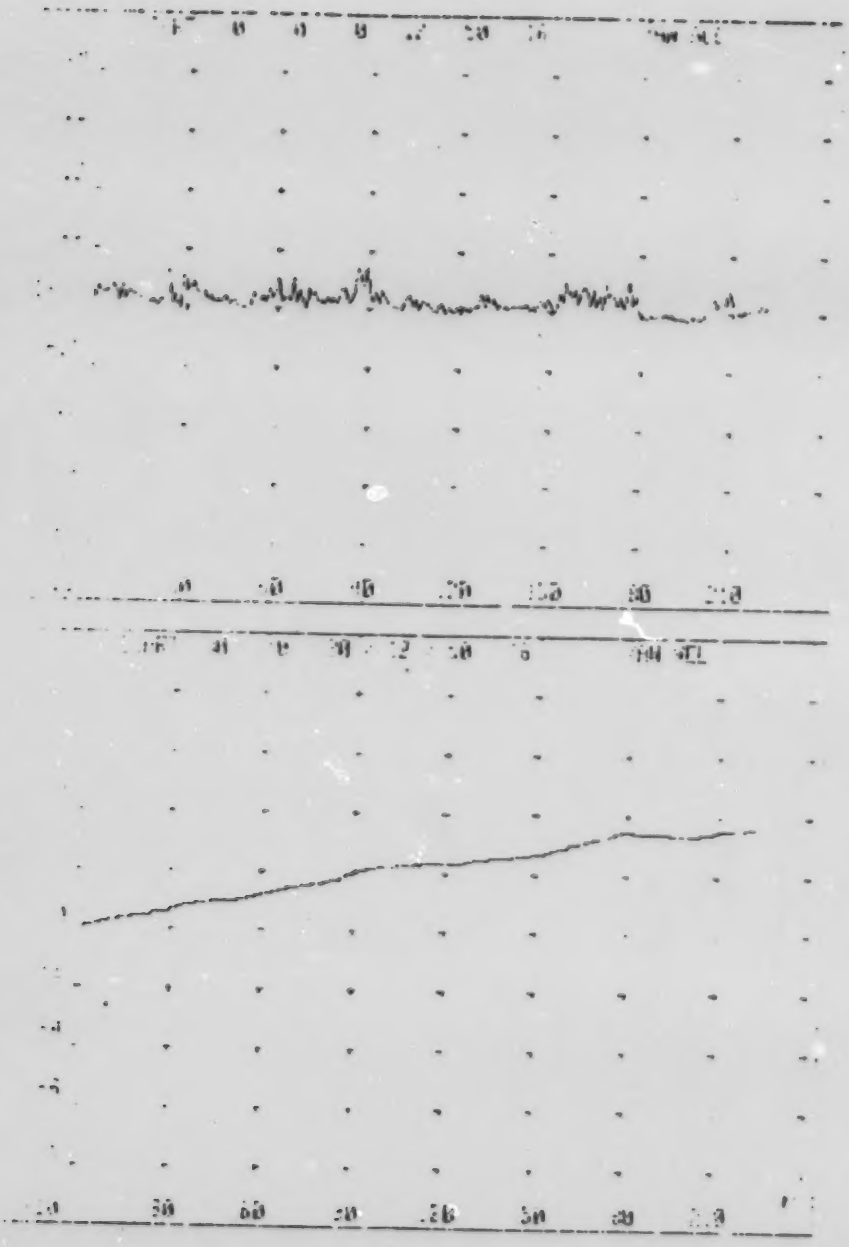
D16





D16

POOR

QUALITY

ORIGINAL